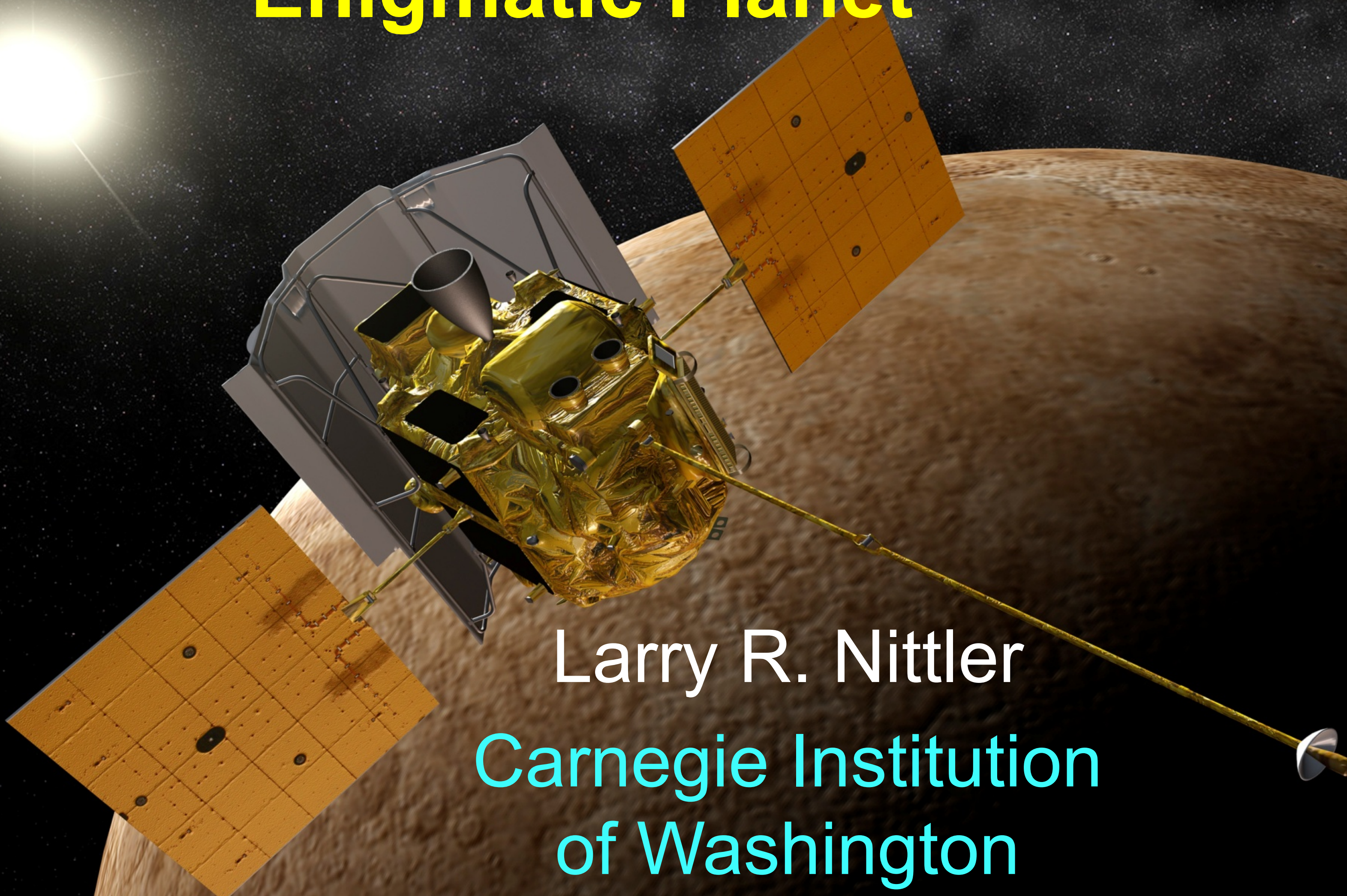
MESSENGER at Mercury: Exploring an Enigmatic Planet

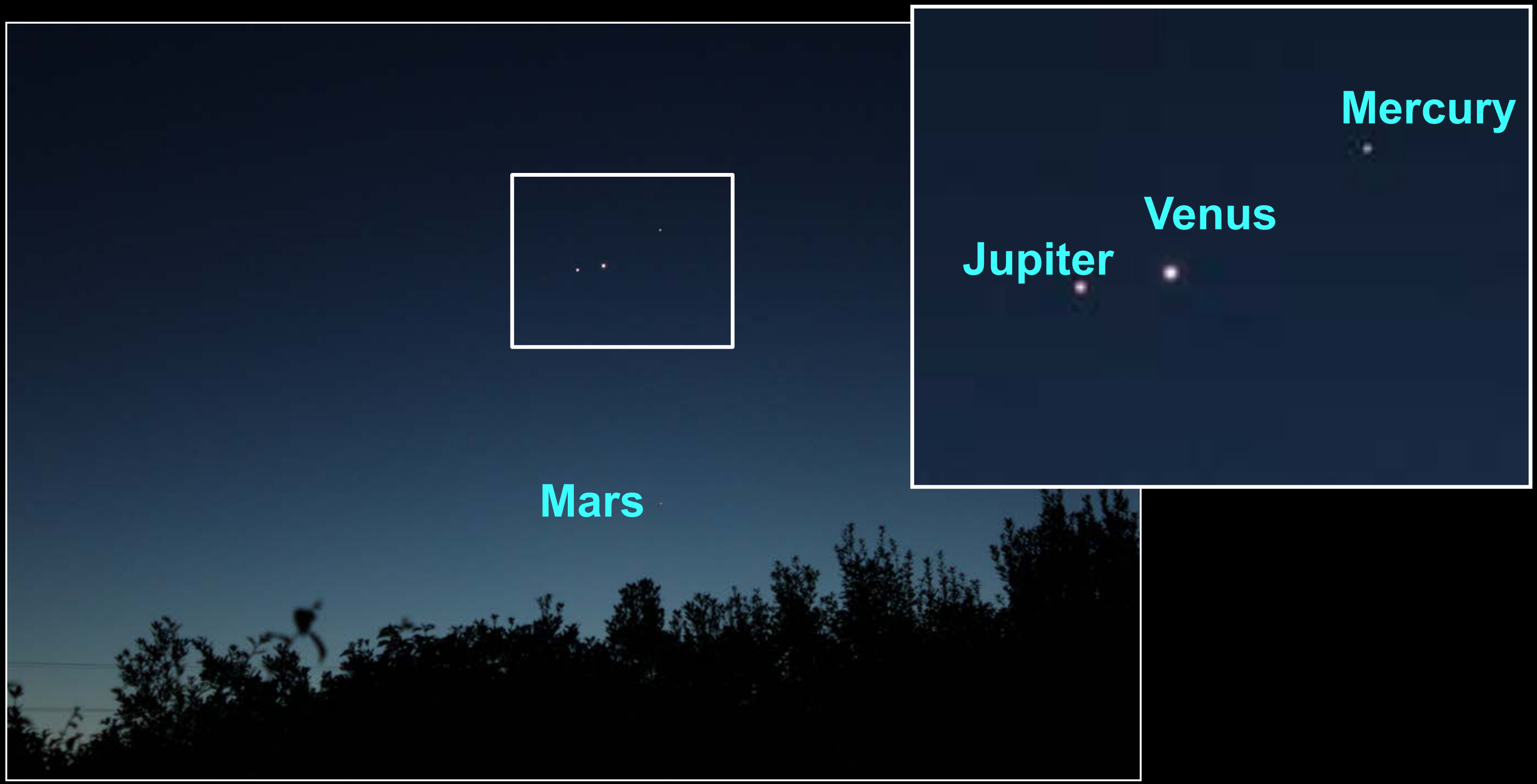


Larry R. Nittler

Carnegie Institution of Washington

Night Sky Network Webinar April 18, 2016

Mercury



May 12, 2011, from NZ (M. White, Flickr)

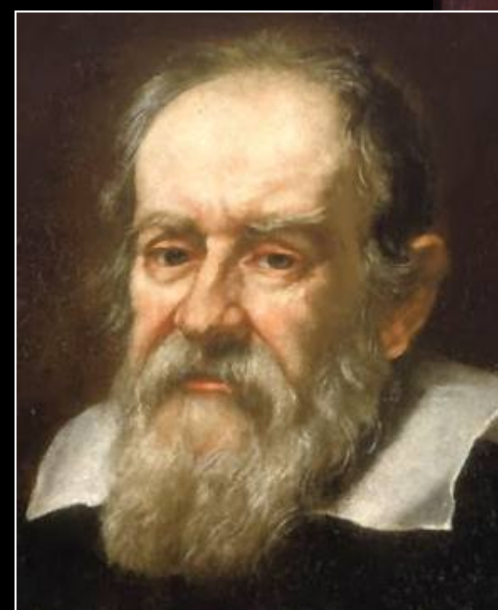
- Naked-eye planet, but very difficult to observe due to proximity to Sun

Early Observations of Mercury

- Greek astronomer Eudoxus correctly measured Mercury's synodic period in ~400 BC
- One early recorded observation (Mesopotamia), Nov. 15, 265 BC
- Earliest telescopic observations by Galileo and Harriot, 1609

Eudoxus of Cnidus, 390 – 340 BC

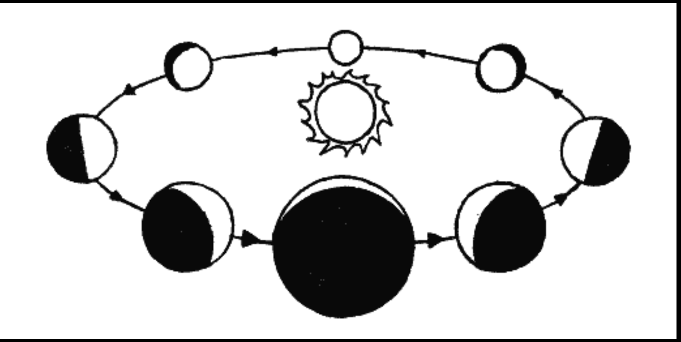
Thomas Harriot, 1560-1621

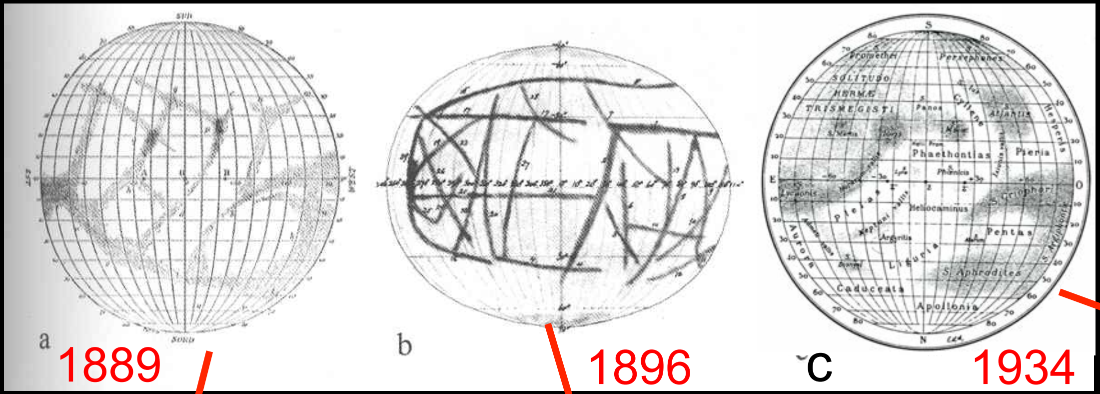


Galileo Galilei, 1564-1642

Early Observations of Mercury

- Discovery of phases by Zupus (1639) proved the Copernican theory that planets orbit the Sun, not the Earth





- Early maps

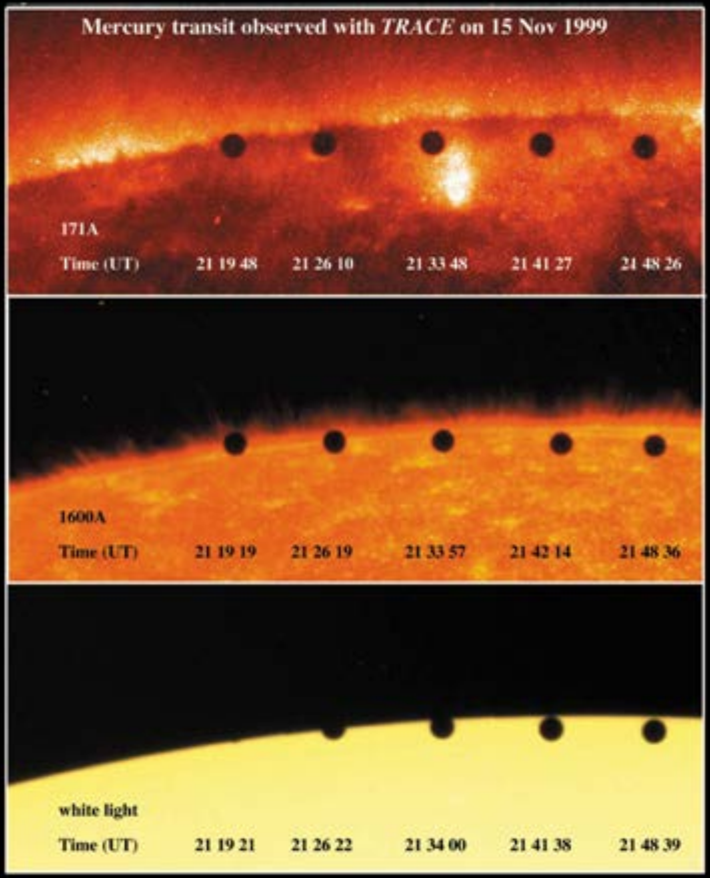
G. Schiaparelli

P. Lowell

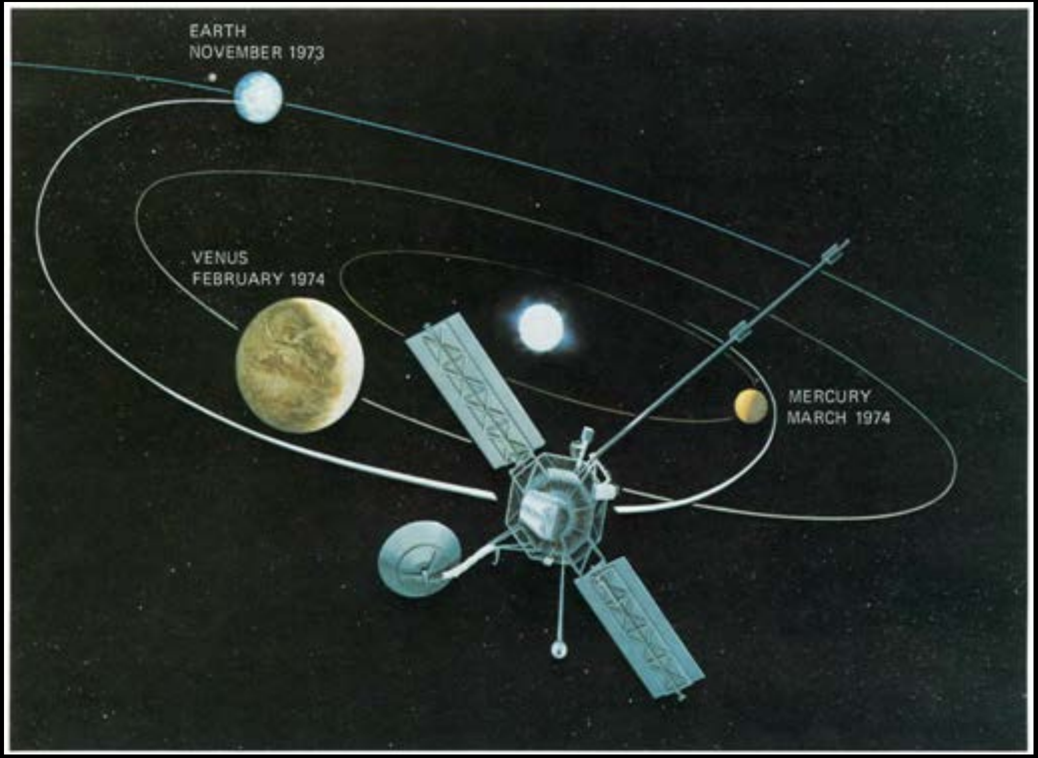
E. Antoniadi

Mercury Is Difficult to Study

…by telescope …



…or spacecraft.



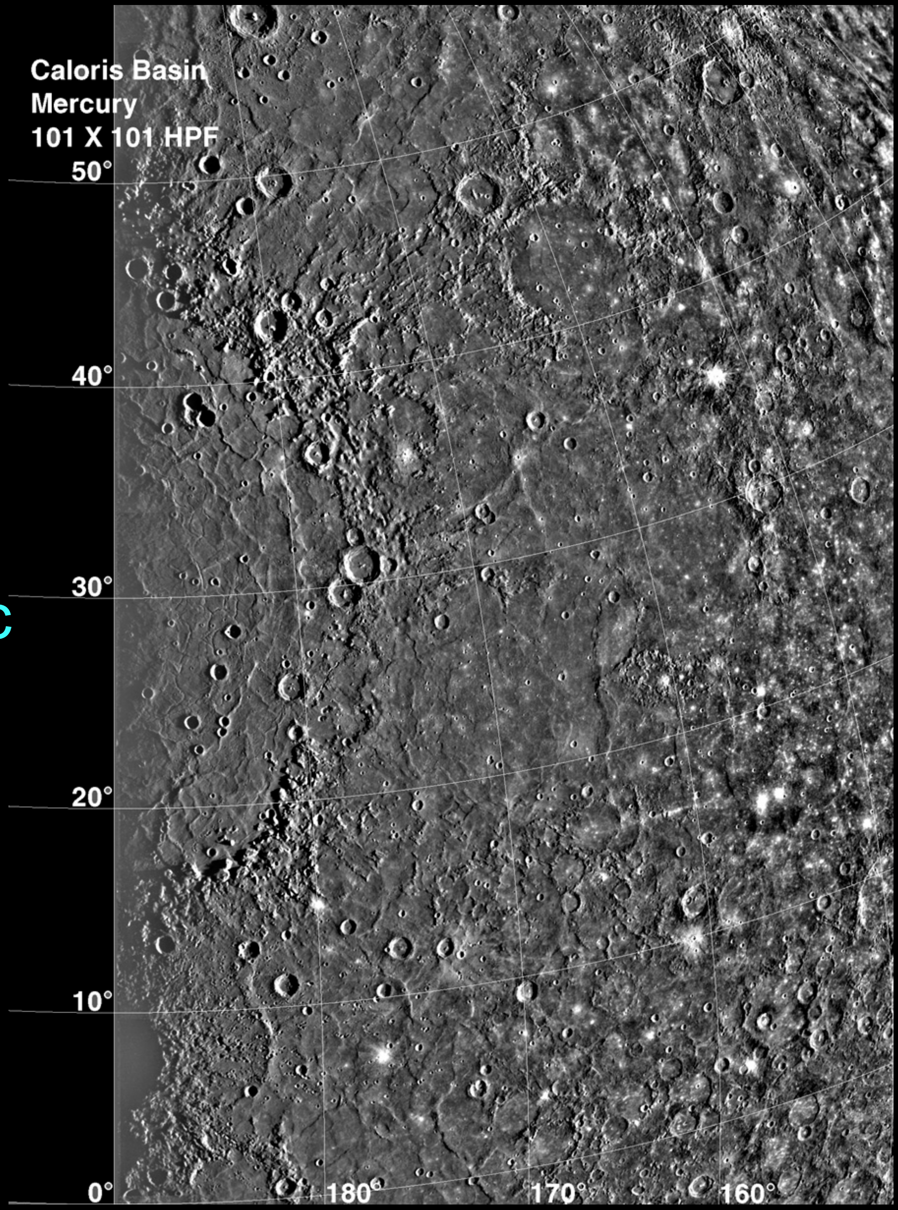
Only prior visit was by

Mariner 10, 1974-1975

Mercury Exploration

Contributions of Mariner 10 flybys:

- Imaged 45% of Mercury's surface
- Discovered Mercury's magnetic field and dynamic magnetosphere
- Detected H, He, O in Mercury's "exosphere"

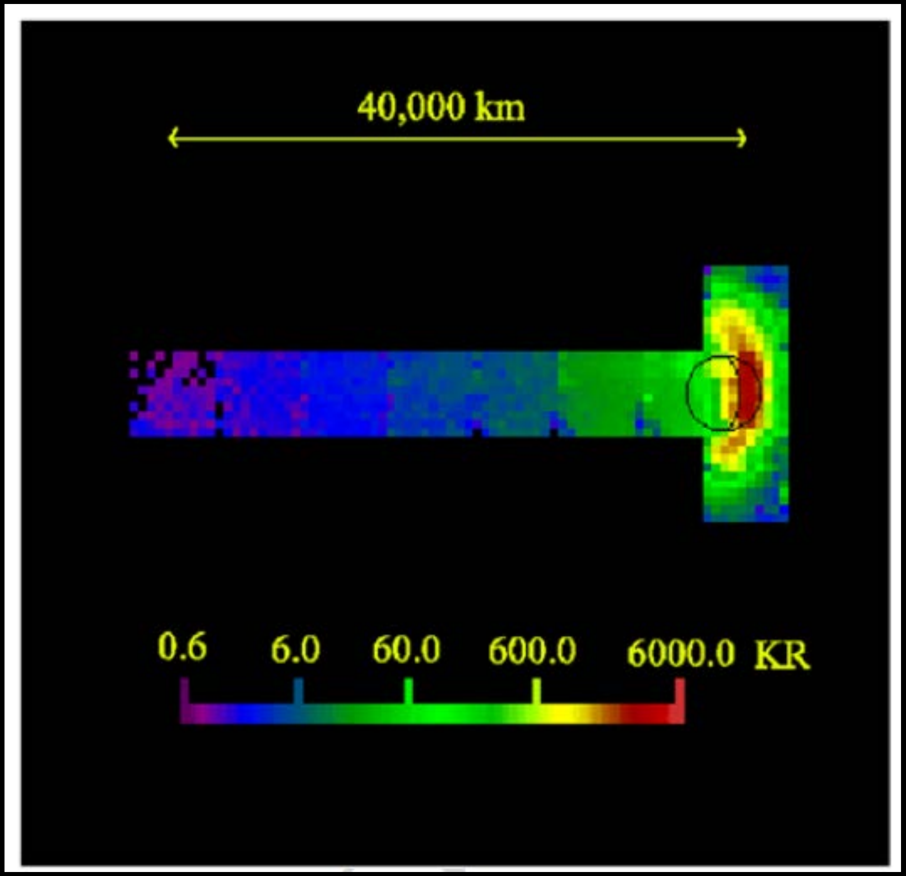


Mariner 10 mosaic of the Caloris basin

Mercury Exploration

Contributions of Earth-based astronomy

- Discovery of Mercury's 3:2 spin-orbit resonance (1965)
  - 3 days in 2 years
- Discovery of sodium (1985), potassium (1986), and calcium (2000) in Mercury's exosphere

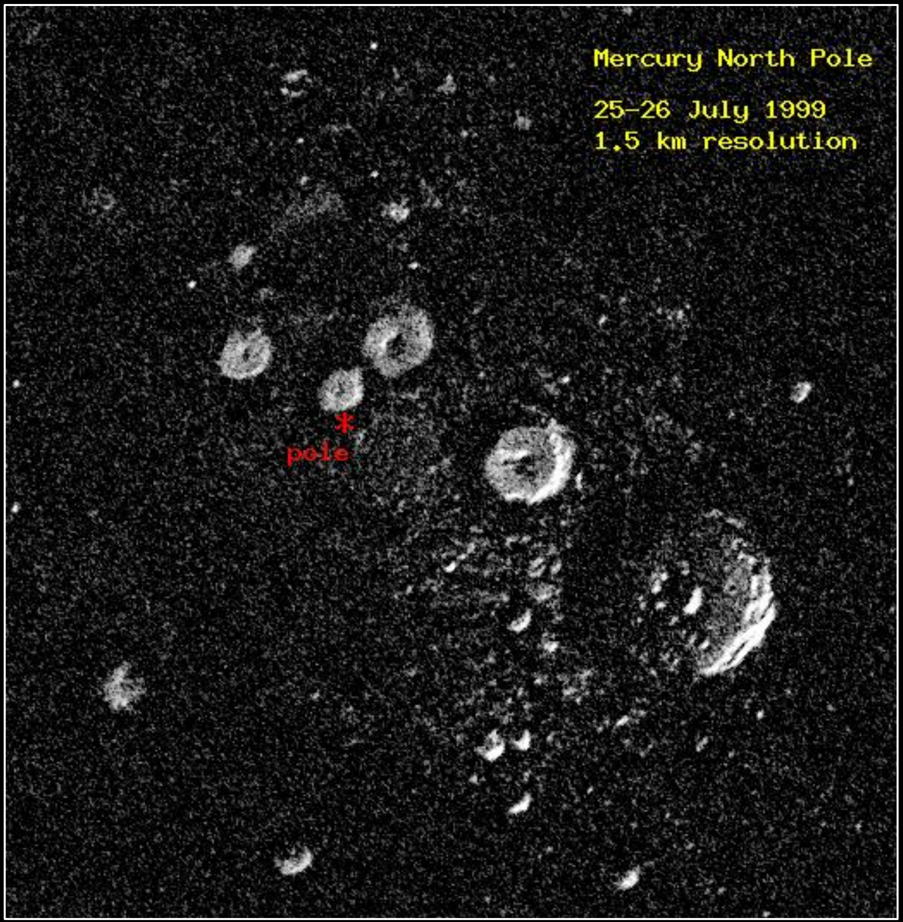


Na emission
Potter et al. 2002

Mercury Exploration

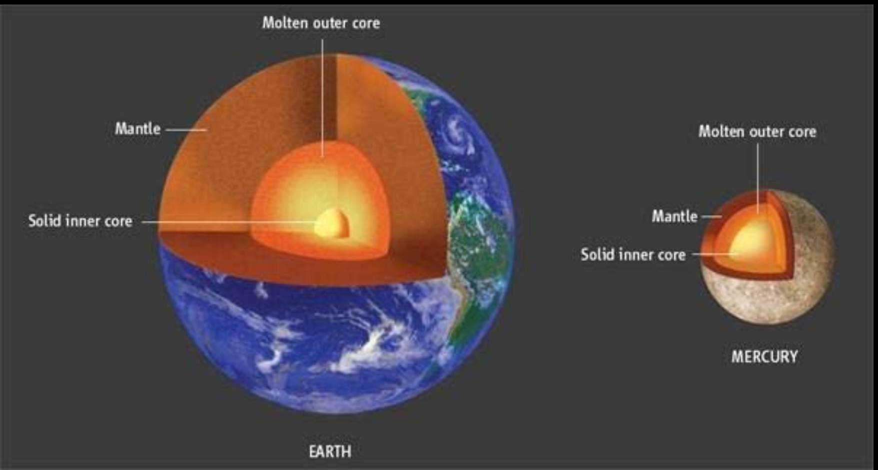
Contributions of Earth-based astronomy

- Discovery of Mercury's polar deposits (1992)
- Discovery of Mercury's molten outer core (2007)



Harmon et al. 1999

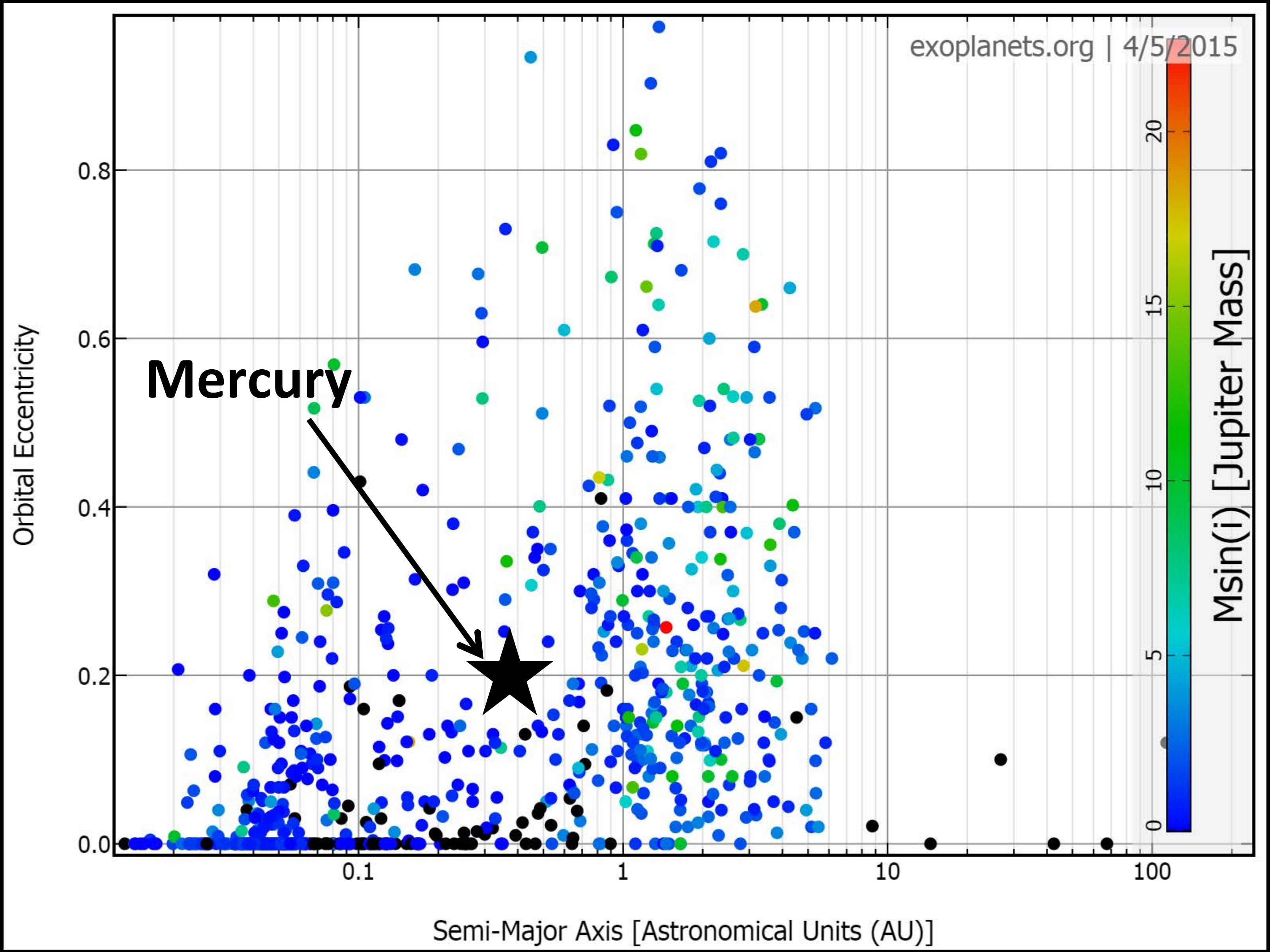
Mercury: planet of extremes



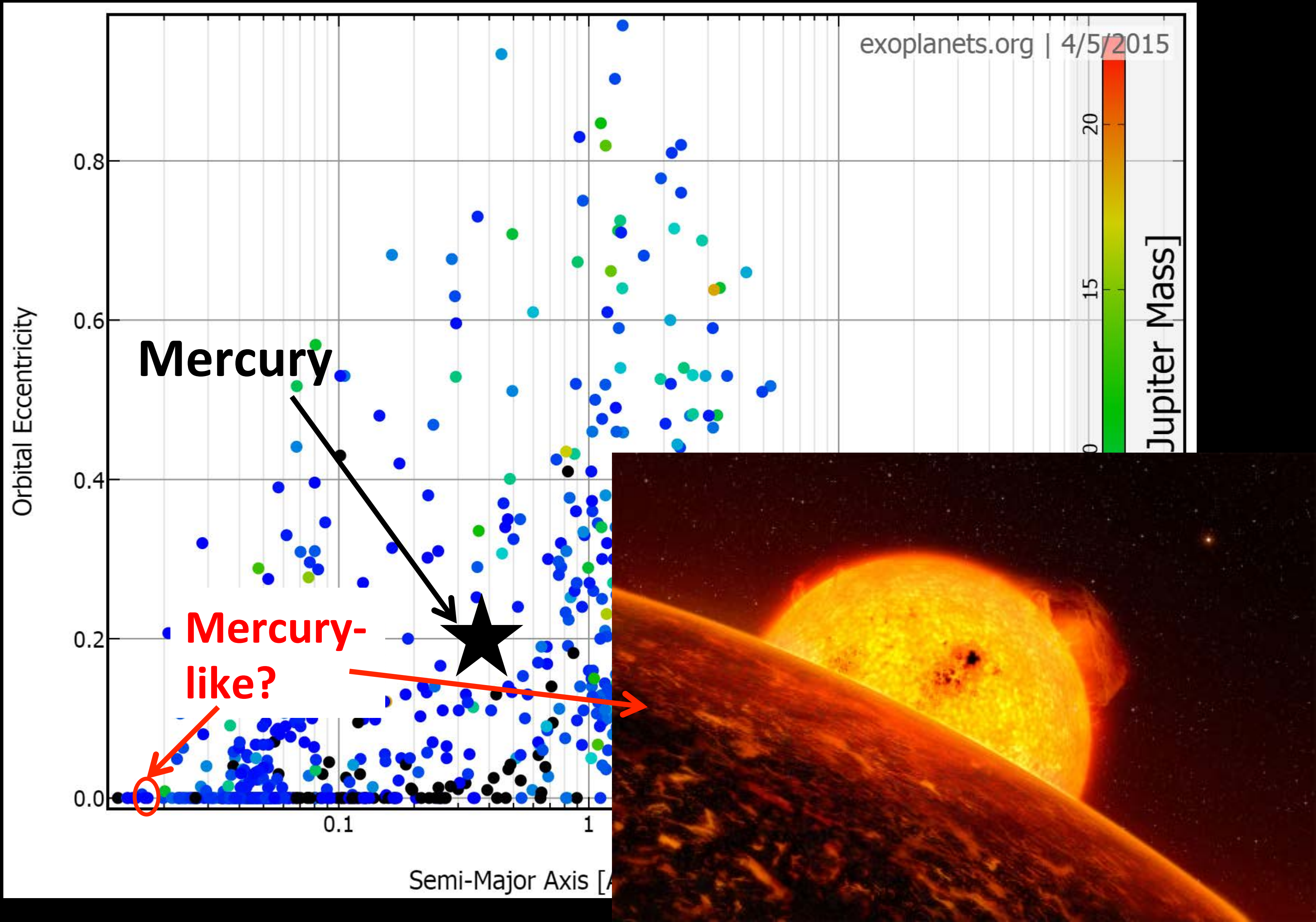
- Smallest, densest planet
- Closest to Sun
- Highest diurnal variation in temperature
  - −170 ºC to +430 ºC
- Very high Fe:silicate ratio
  - Core ~70% of mass, 80% radius
- Mercury and Earth are the only inner planets with magnetic fields

“end-member of planet formation”

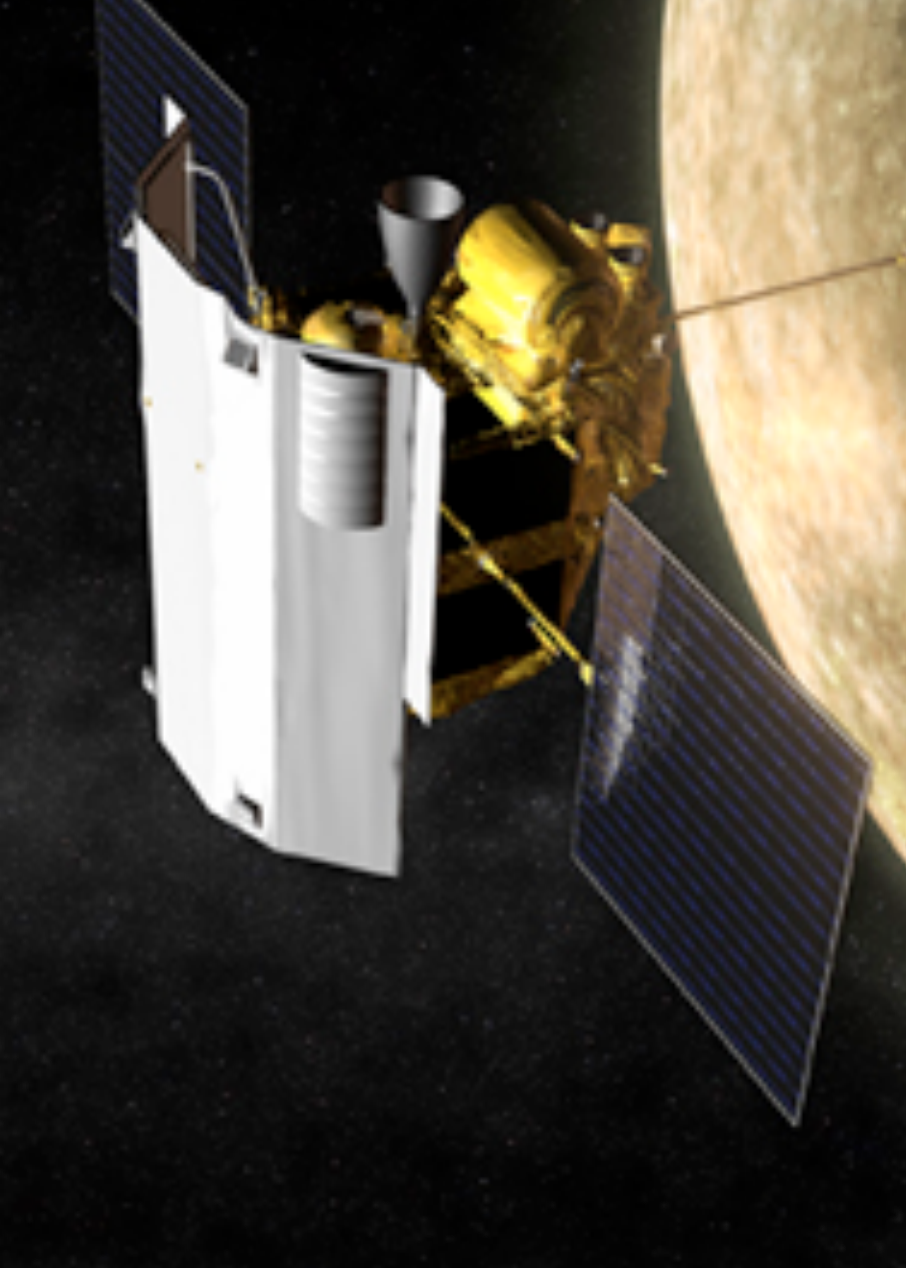
Extrasolar Planetary Context



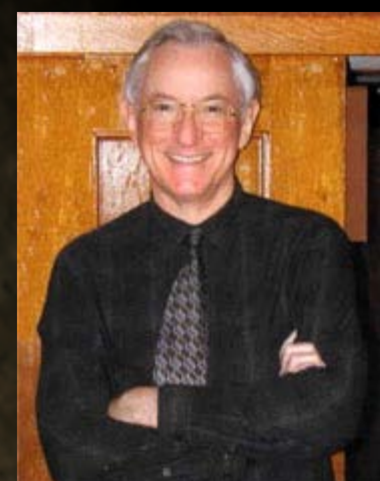
Extrasolar Planetary Context



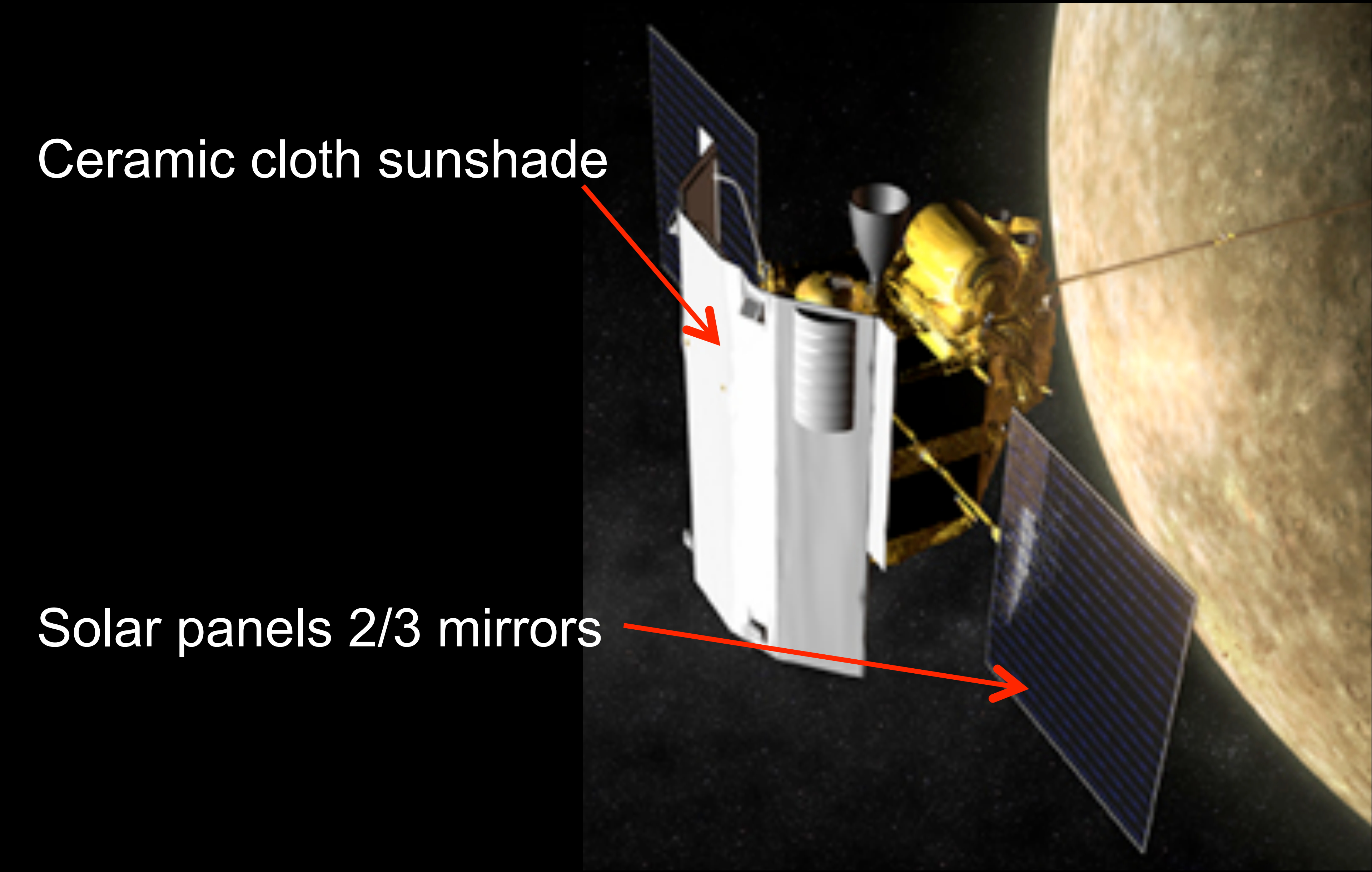
MESSENGER



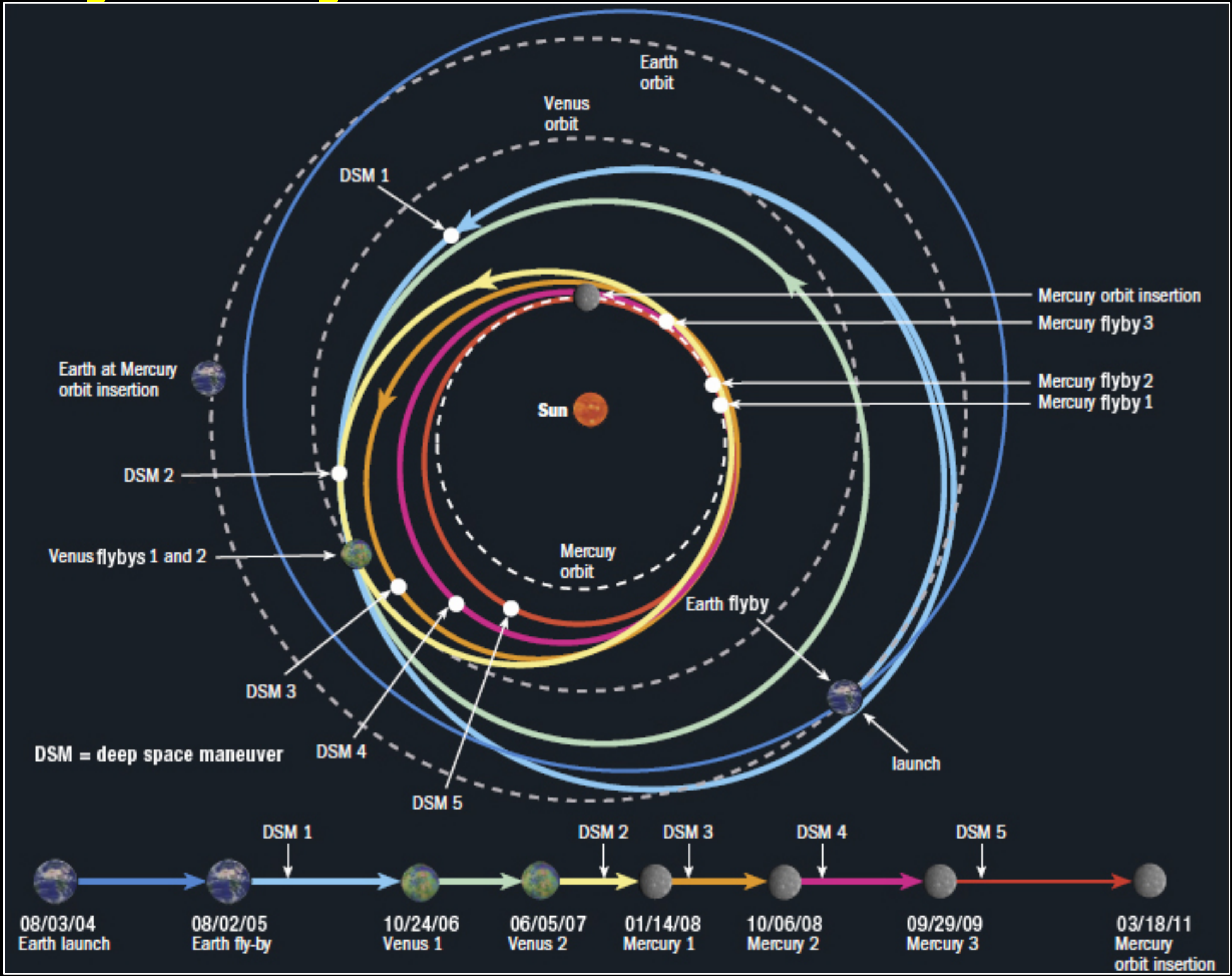
- First spacecraft to orbit Mercury
- 7^{th} NASA *Discovery* mission
  - PI: Sean C. Solomon



Challenge: Surviving at Mercury



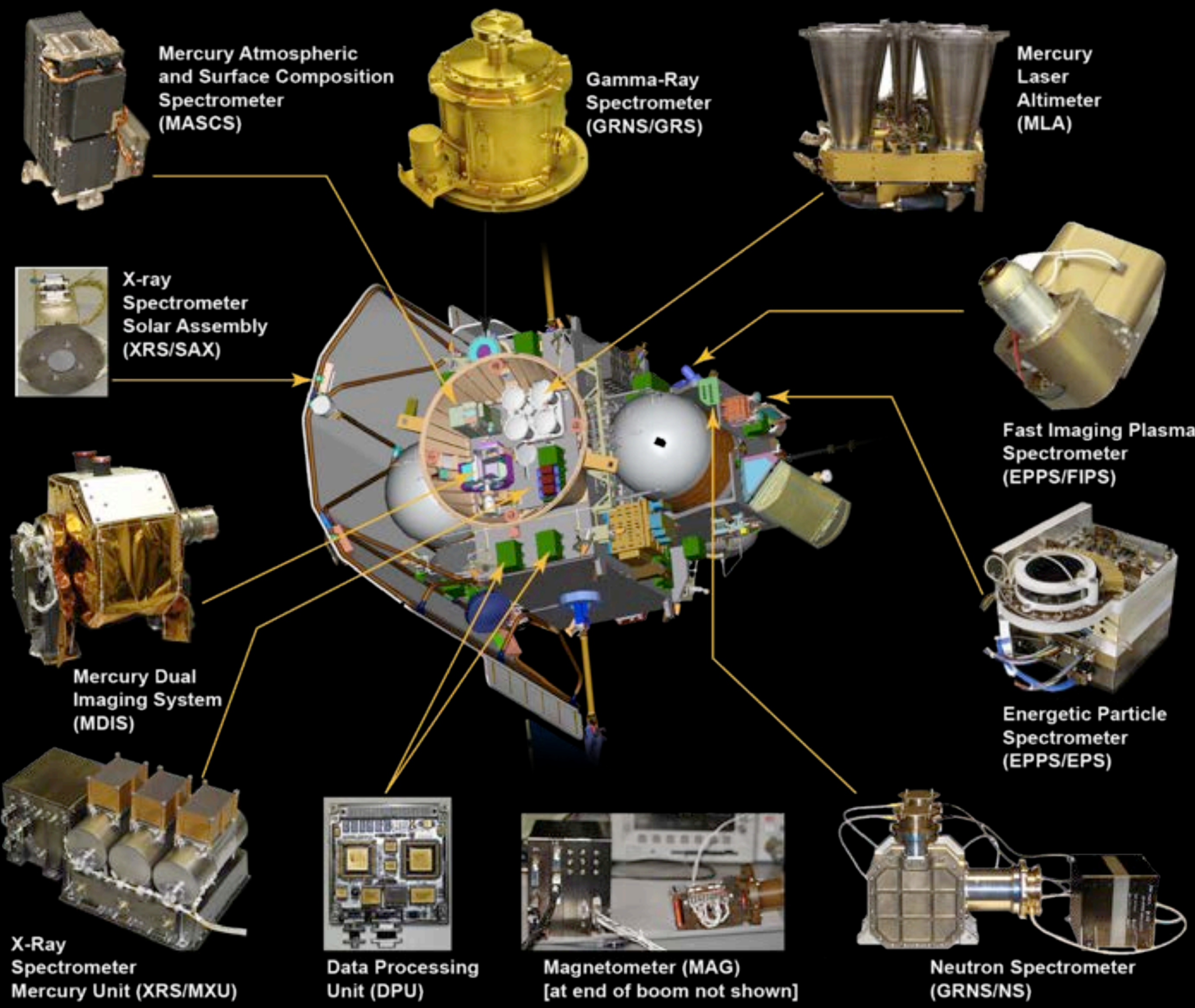
Trajectory allowed orbit insertion



MESSENGER's Guiding Science Questions mapped to Measurement Objectives

Science Questions	MESSENGER Measurement Objectives
Why is Mercury so dense?	Map the elemental and mineralogical composition of Mercury's surface
What is the geological history of Mercury?	Globally image the surface at a resolution of hundreds of meters or better
What are the nature and origin of Mercury's magnetic field?	Determine the structure of the planet's magnetic field
What are the structure and state of Mercury's core?	Measure the libration amplitude and gravitational field structure
What are the radar-reflective materials at Mercury's poles?	Determine the composition of the radar-reflective materials at Mercury's poles
What are the important volatile species and their sources and sinks near Mercury?	Characterize exosphere neutrals and accelerated magnetosphere ions

MESSENGER's Scientific Payload



Vibration test, December 2003

Launch, August 2004

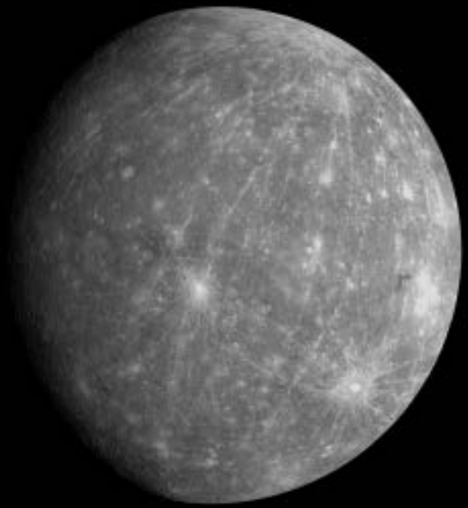
Getting to Mercury

Earth (August 2005)

Venus (October 2006)

Mercury Flybys (2008-2009)

M1 (Jan 2008)

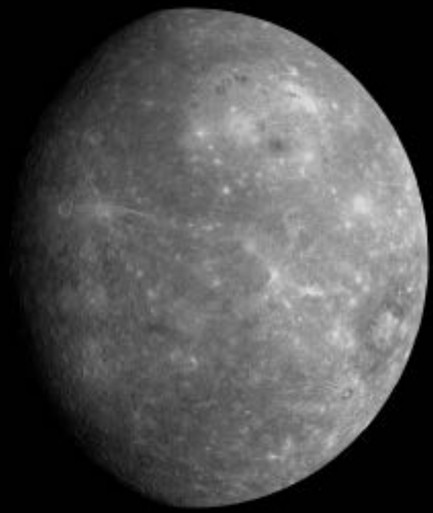


M2 (Oct 2008)

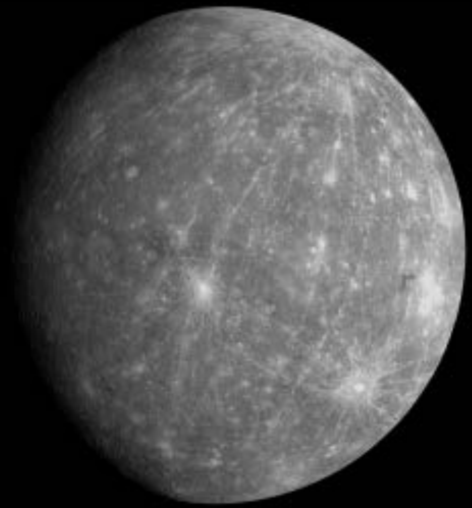
- >90% of surface imaged

M3 (Sep 2009)

Mercury Flybys (2008-2009)

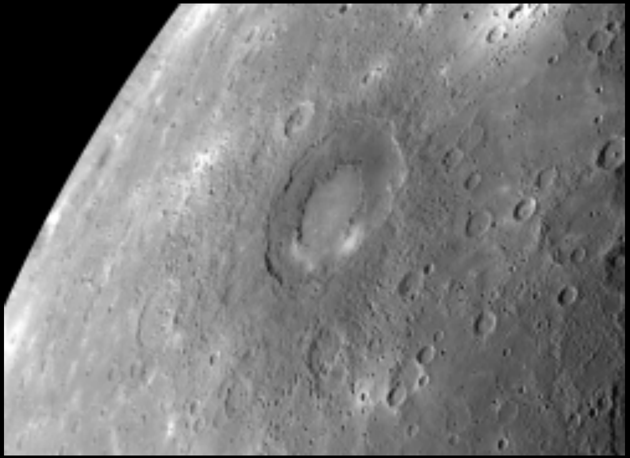


M1 (Jan 2008)



M2 (Oct 2008)

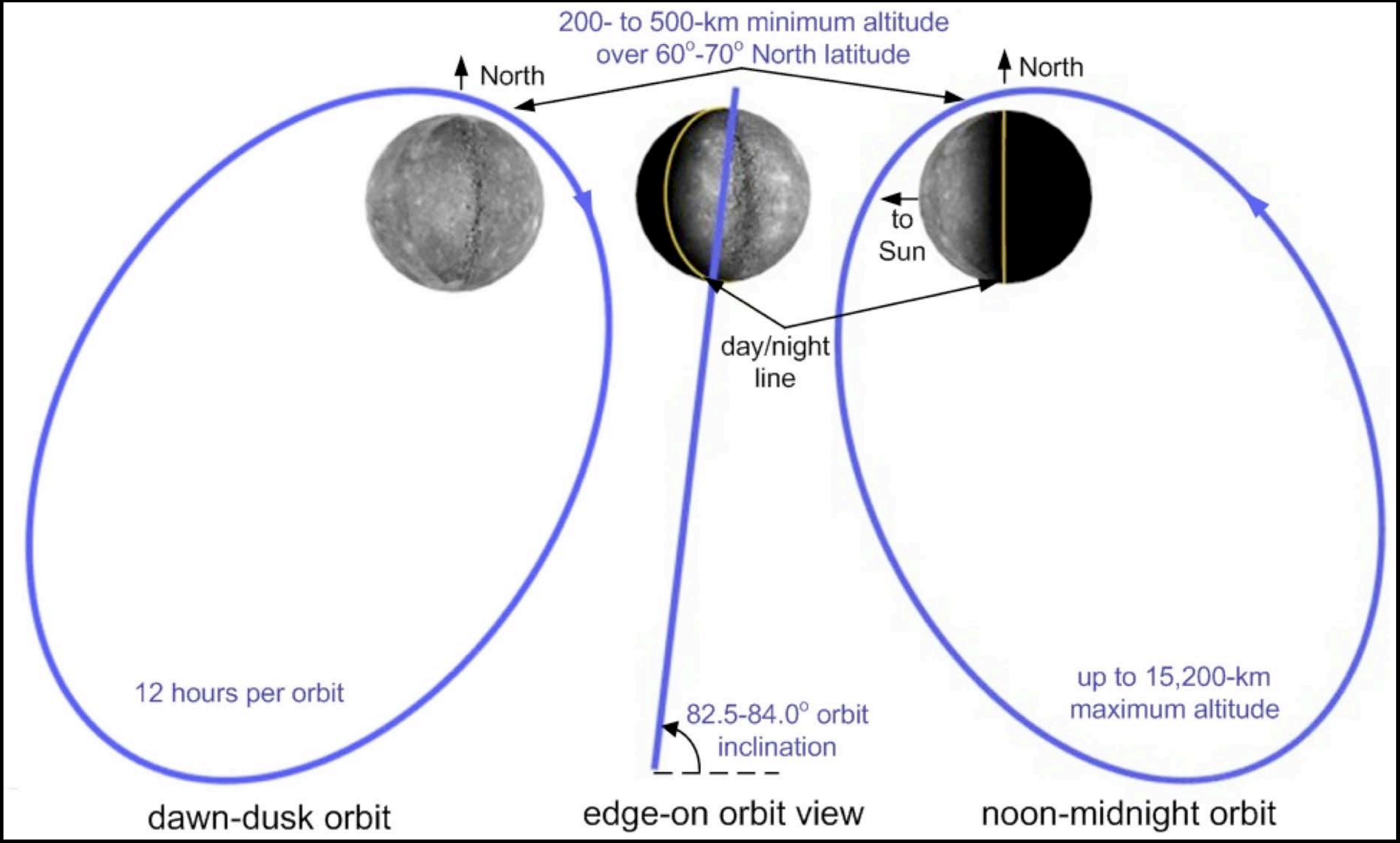
- >90% of surface imaged



M3 (Sep 2009)

Mission also first spacecraft to use solar sailing!

Mercury Orbit Insertion (March 18, 2011)



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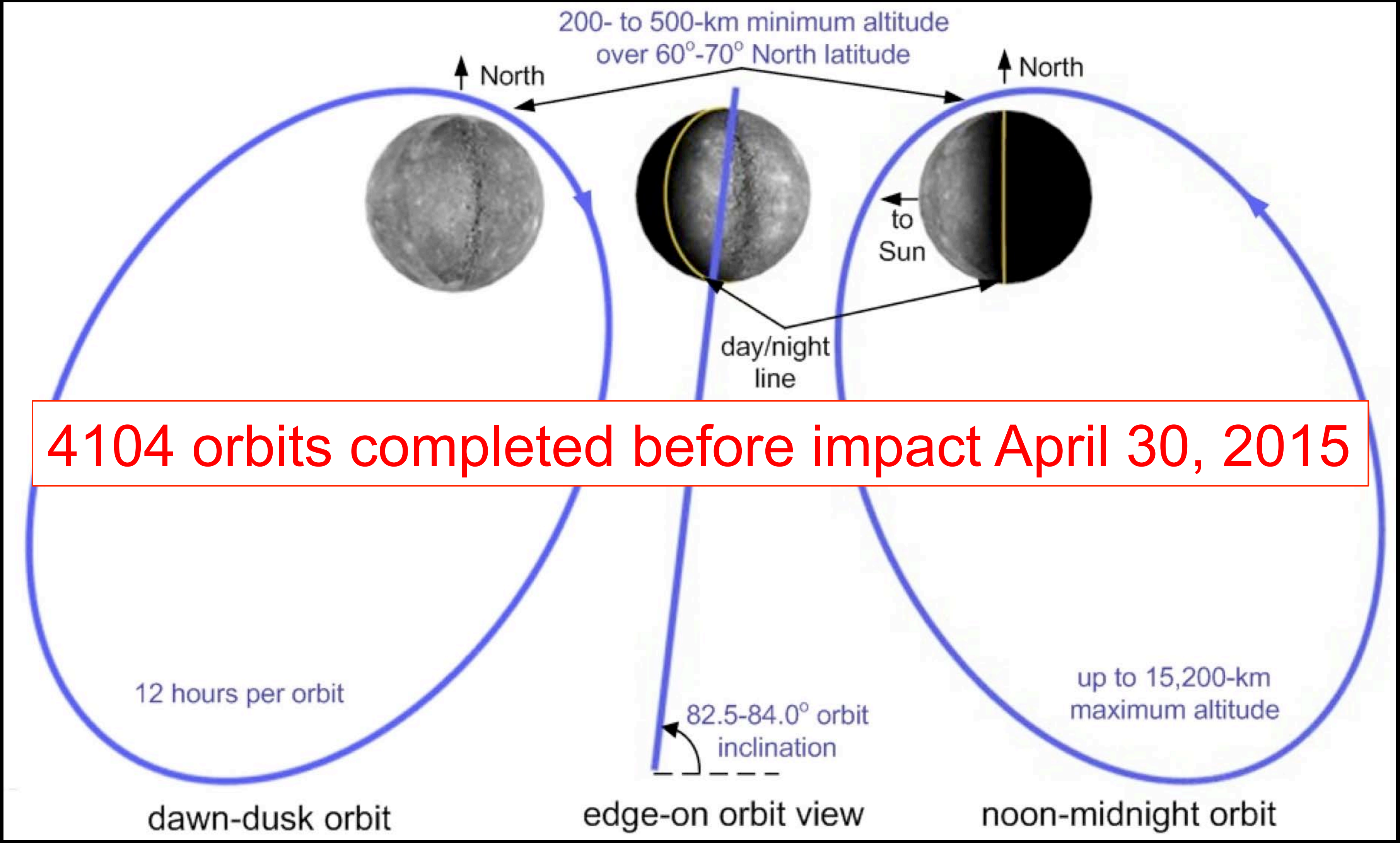


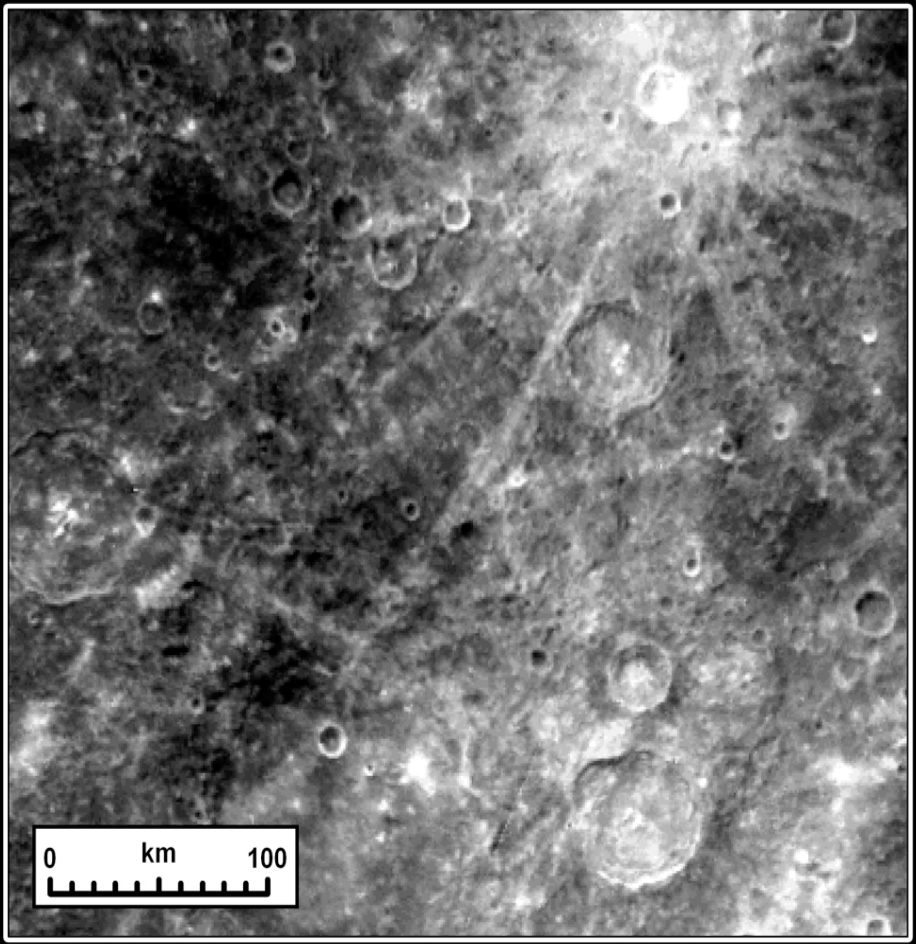
4104 orbits completed before impact April 30, 2015

Feb 2013: MESSENGER imaging coverage reached 100%

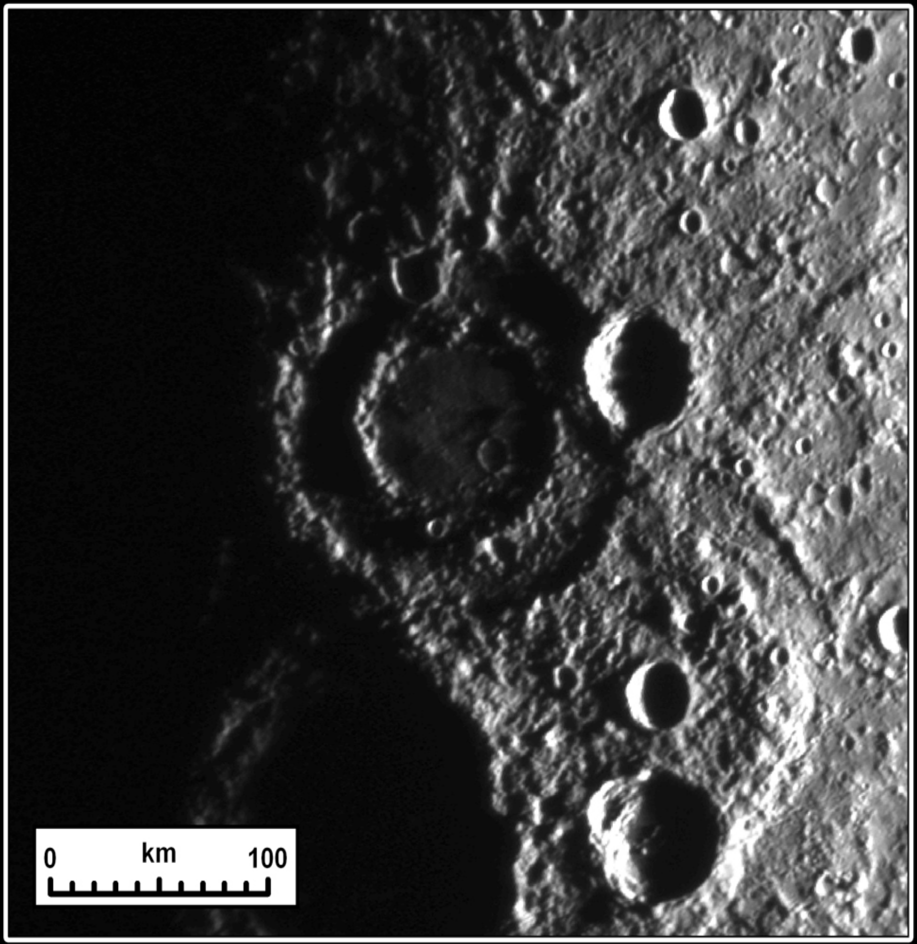
Mercury in “true” color – RGB: 630, 560, 480 nm

Mercury in “enhanced” color – RGB: PC2, PC1, 430/1000

Illumination Matters

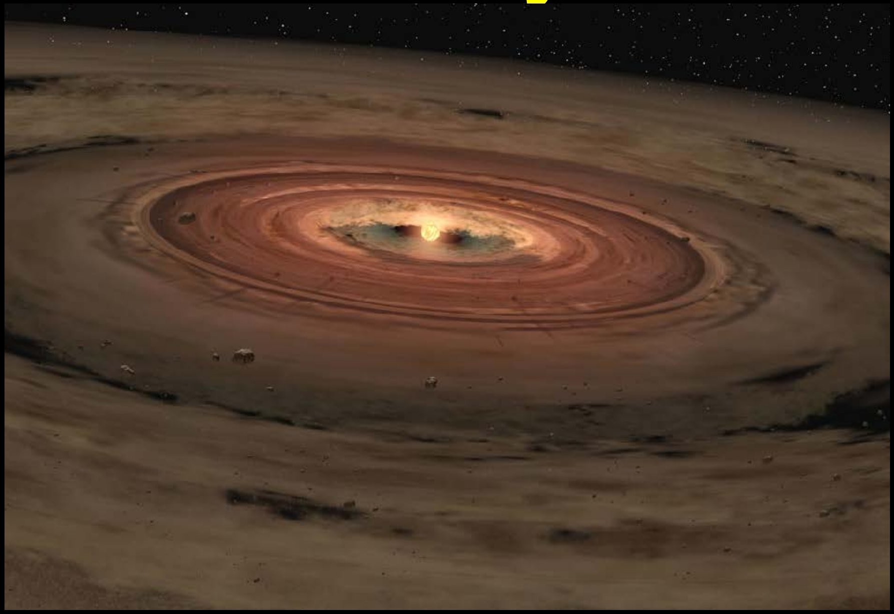


MARINER 10



MESSENGER

Formation of Mercury



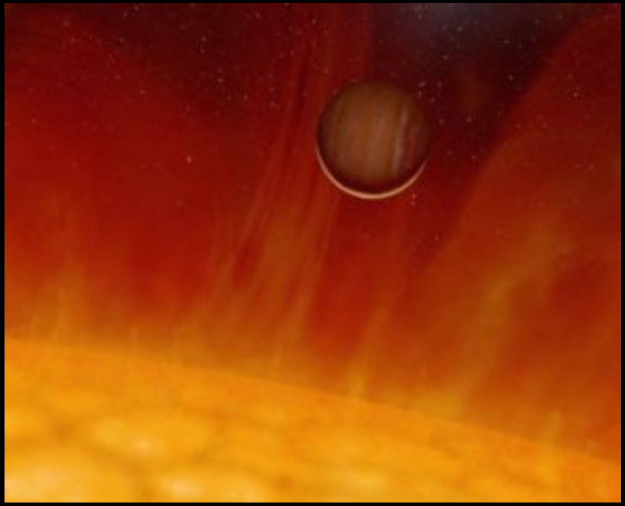
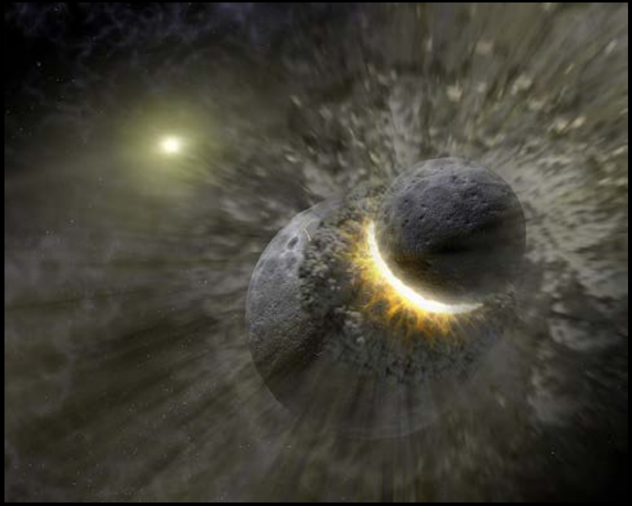
- Terrestrial planets shared common formation process:
  accretion

Dust -> Rocks -> Planetesimals -> Planets

- Why does Mercury have such a large Fe core?

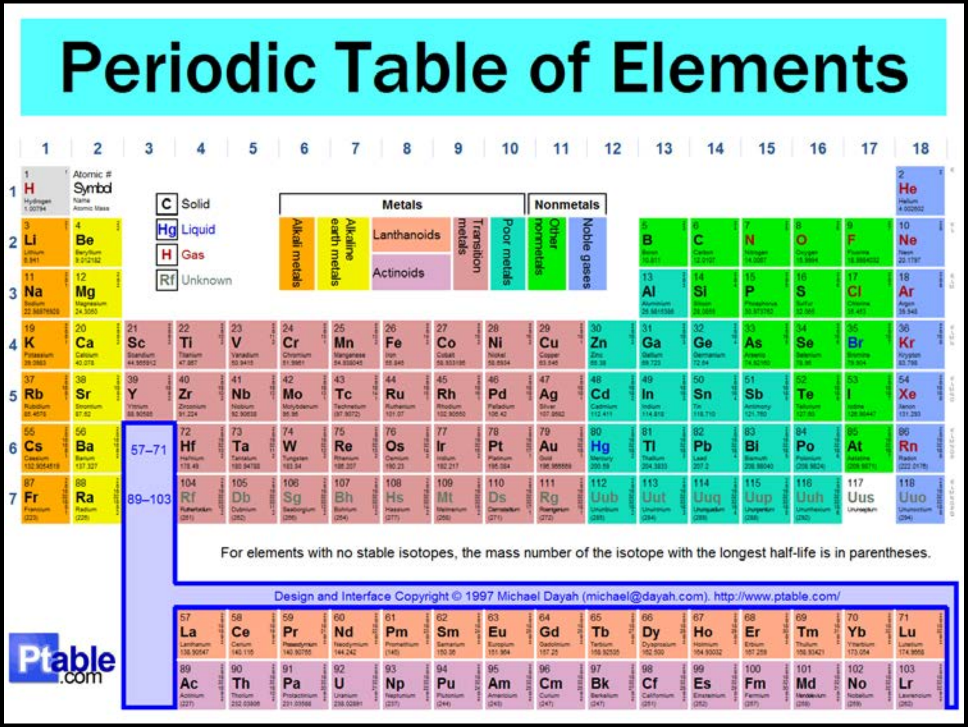
(pre-MESSENGER) Mercury Formation Models

- Accretion at high-T? (Lewis 1973)
- Evaporation by hot Sun? (Cameron 1985)
- Giant impact stripping? (Wetherill, Benz 1988)
- Metal-silicate segregation (Weidenschilling 1978)

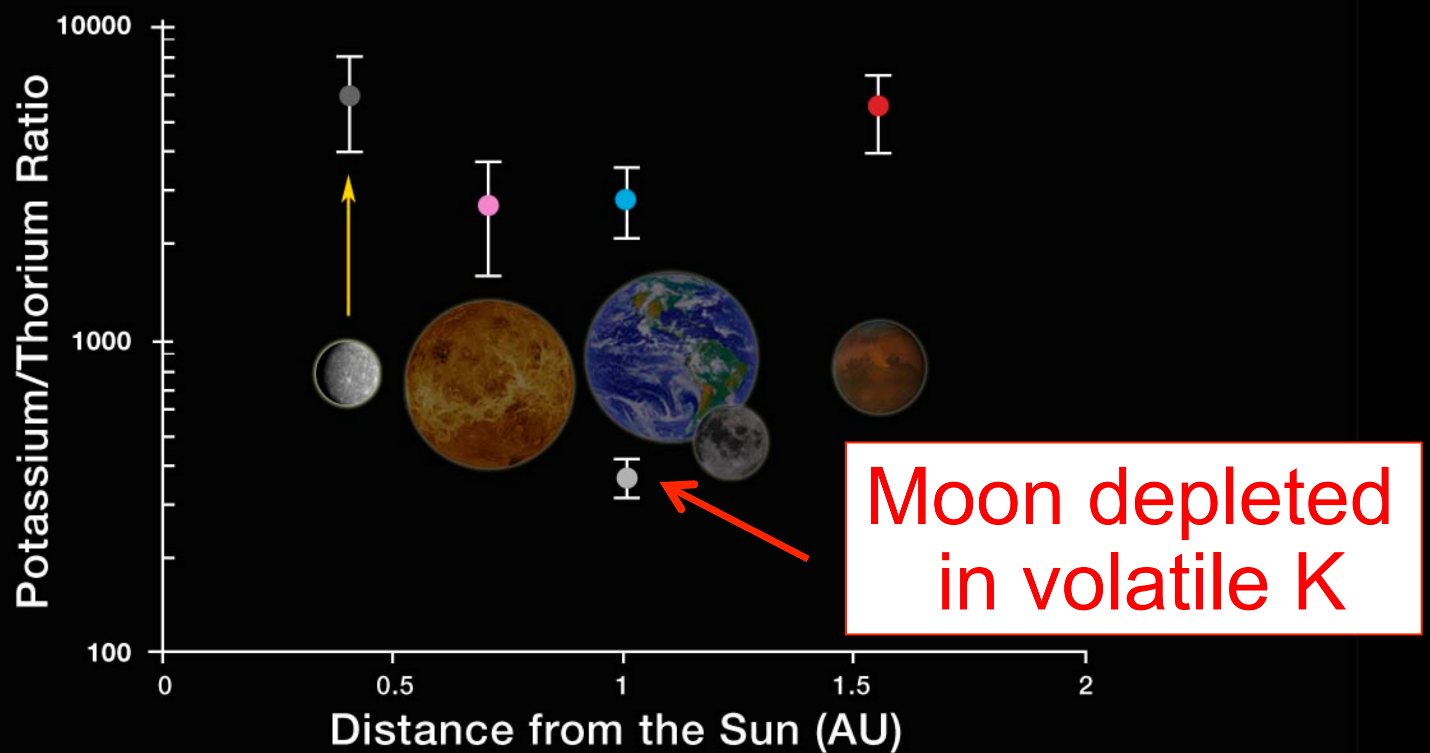



Composition is key

- Surface elemental composition depends on starting materials and history
- MESSENGER had 3 instruments for measuring surface composition
  - X-ray Spectrometer (XRS)
  - Gamma-ray Spectrometer (GRS)
  - Neutron Spectrometer (NS)



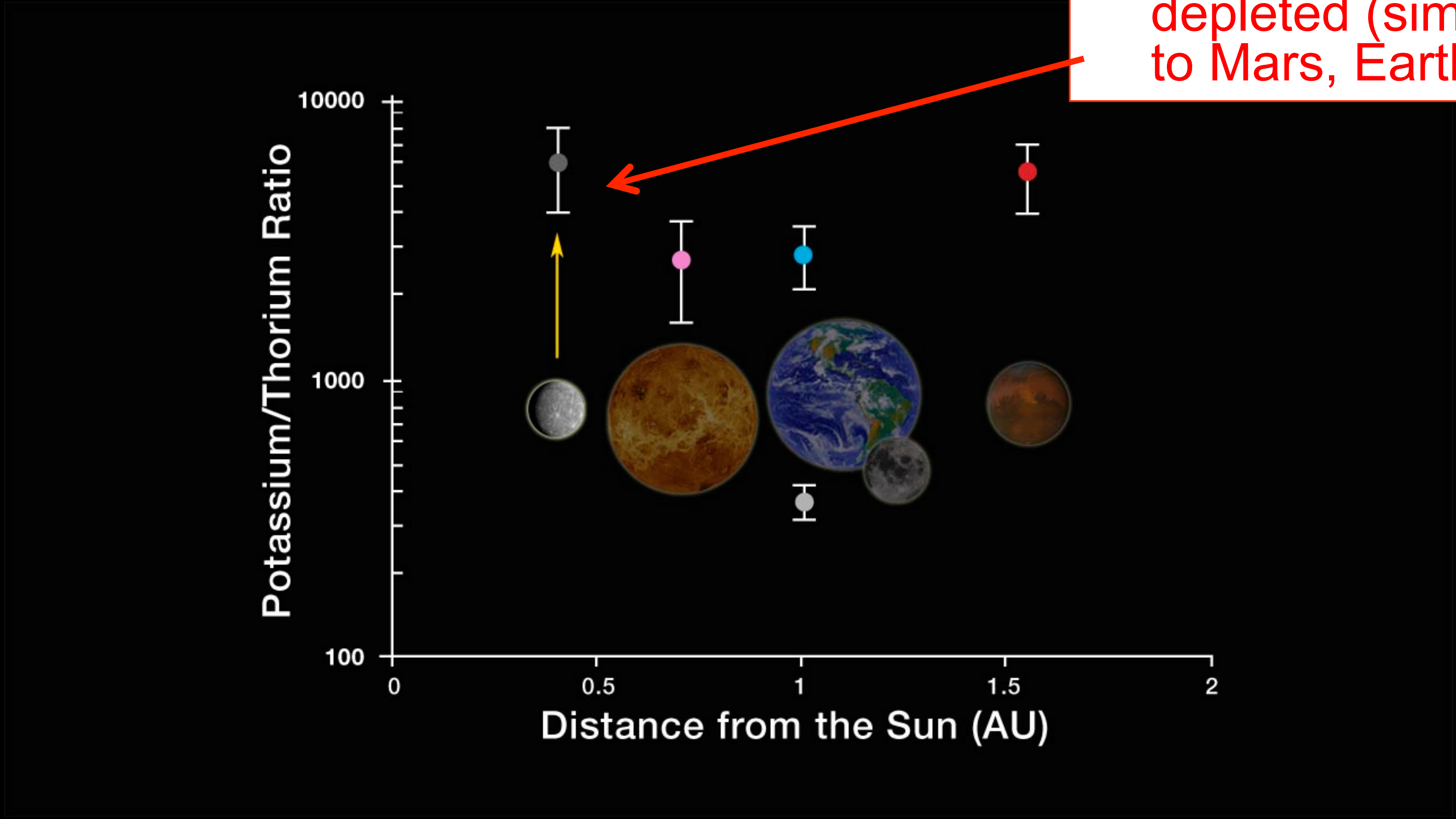
Volatile Elements on Mercury



(Peplowski et al., 2011,2012)

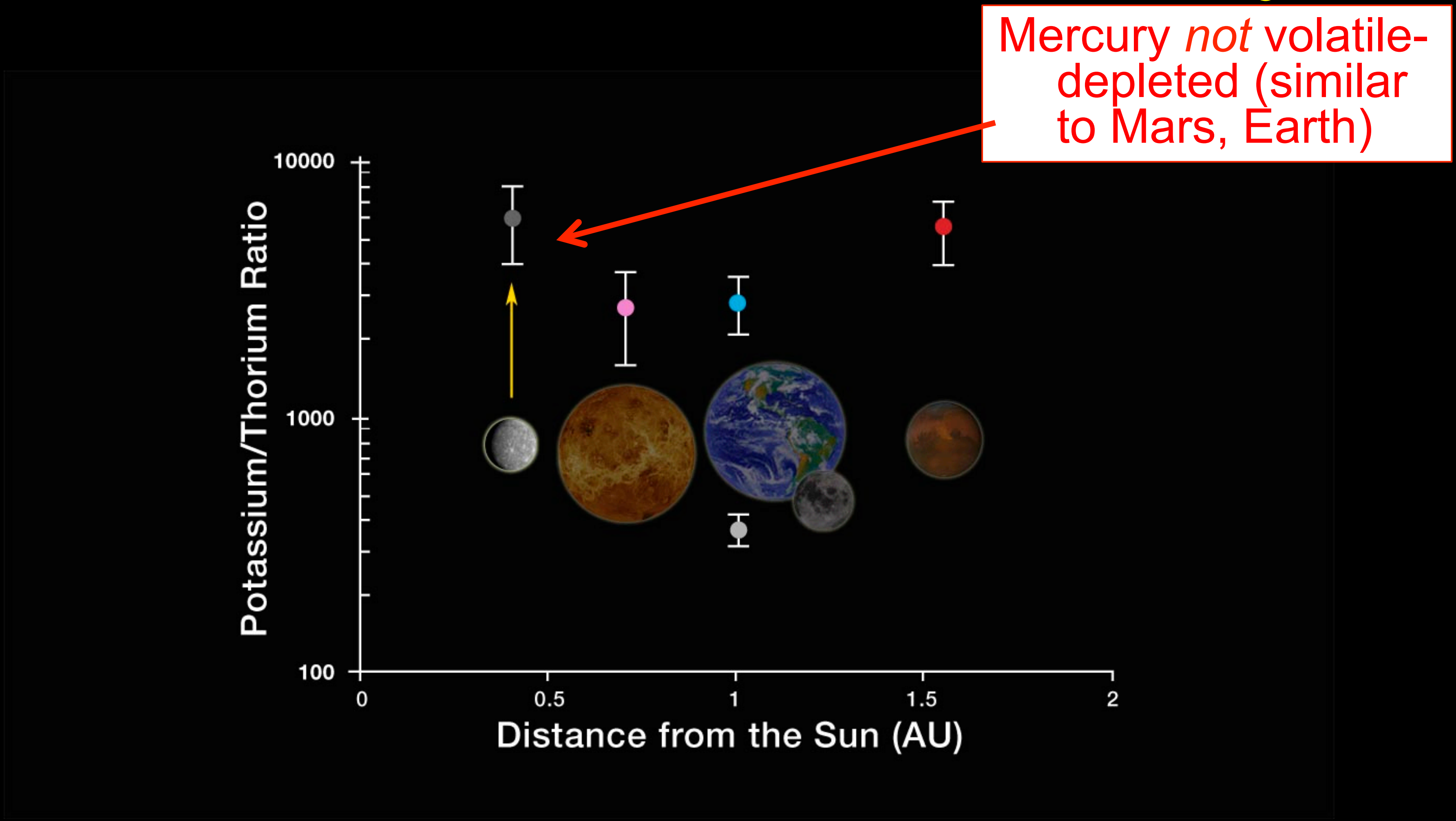
Volatile Elements on Mercury

Mercury *not* volatile-depleted (similar to Mars, Earth)



(Peplowski et al., 2011,2012)

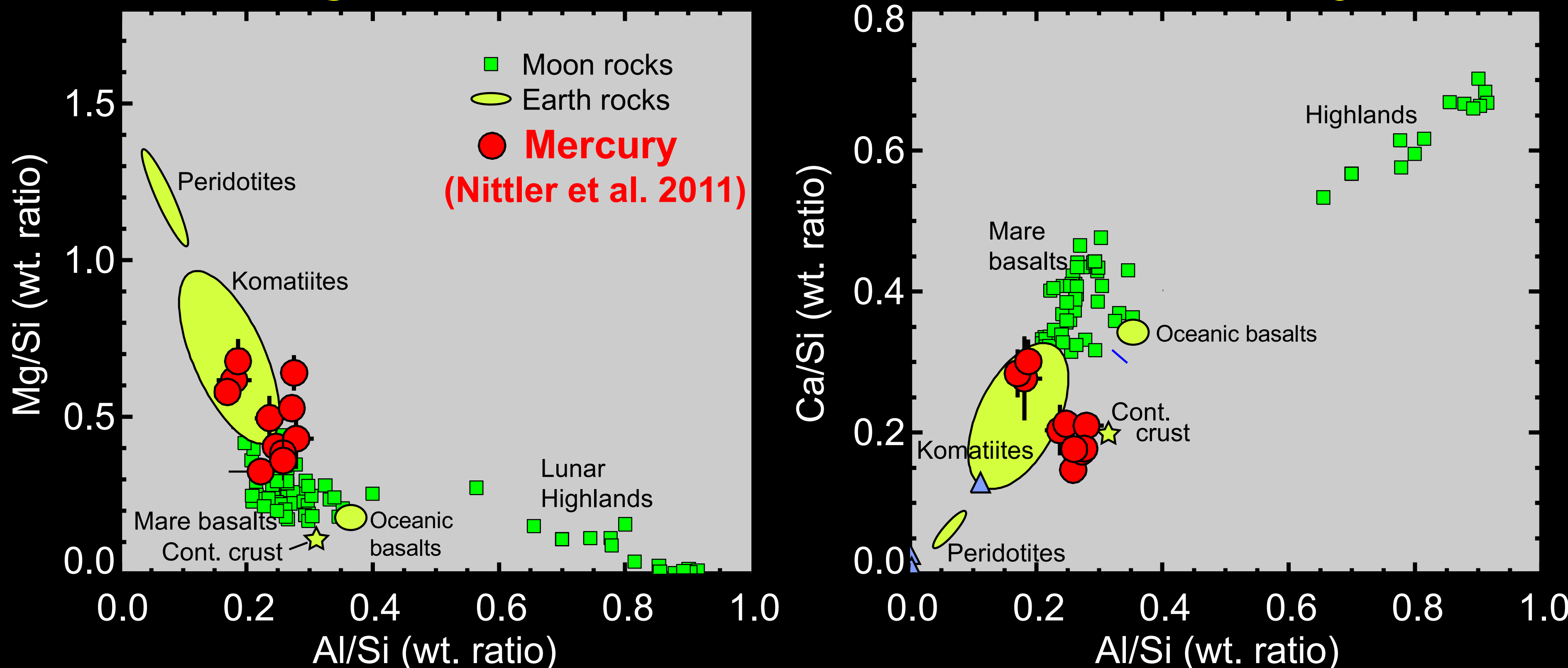
Volatile Elements on Mercury



(Peplowski et al., 2011,2012)

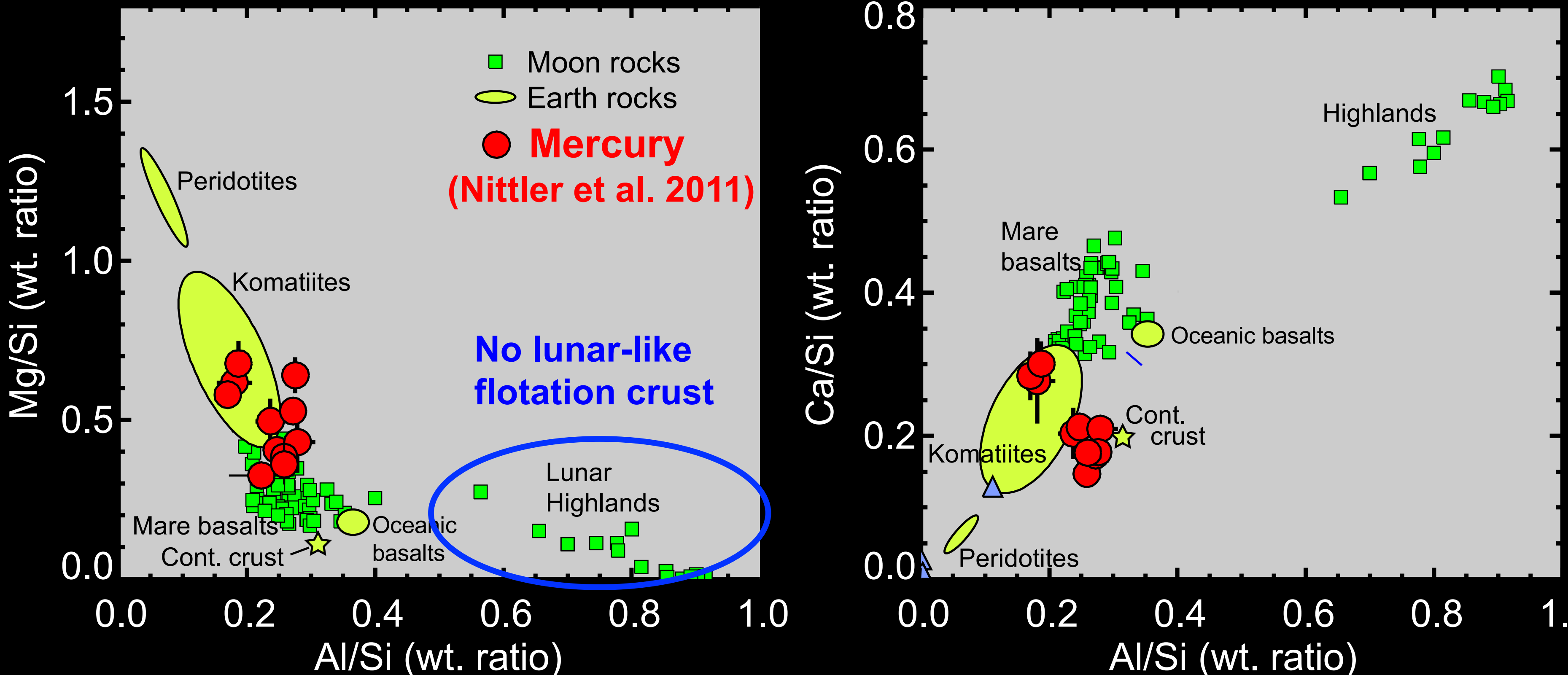
Also rich in volatiles Na and Cl!

Major elements on Mercury



- X-ray Spectrometer data indicate Mercury Mg-rich, Al-Ca-poor, relative to Earth and Moon surface

Major elements on Mercury



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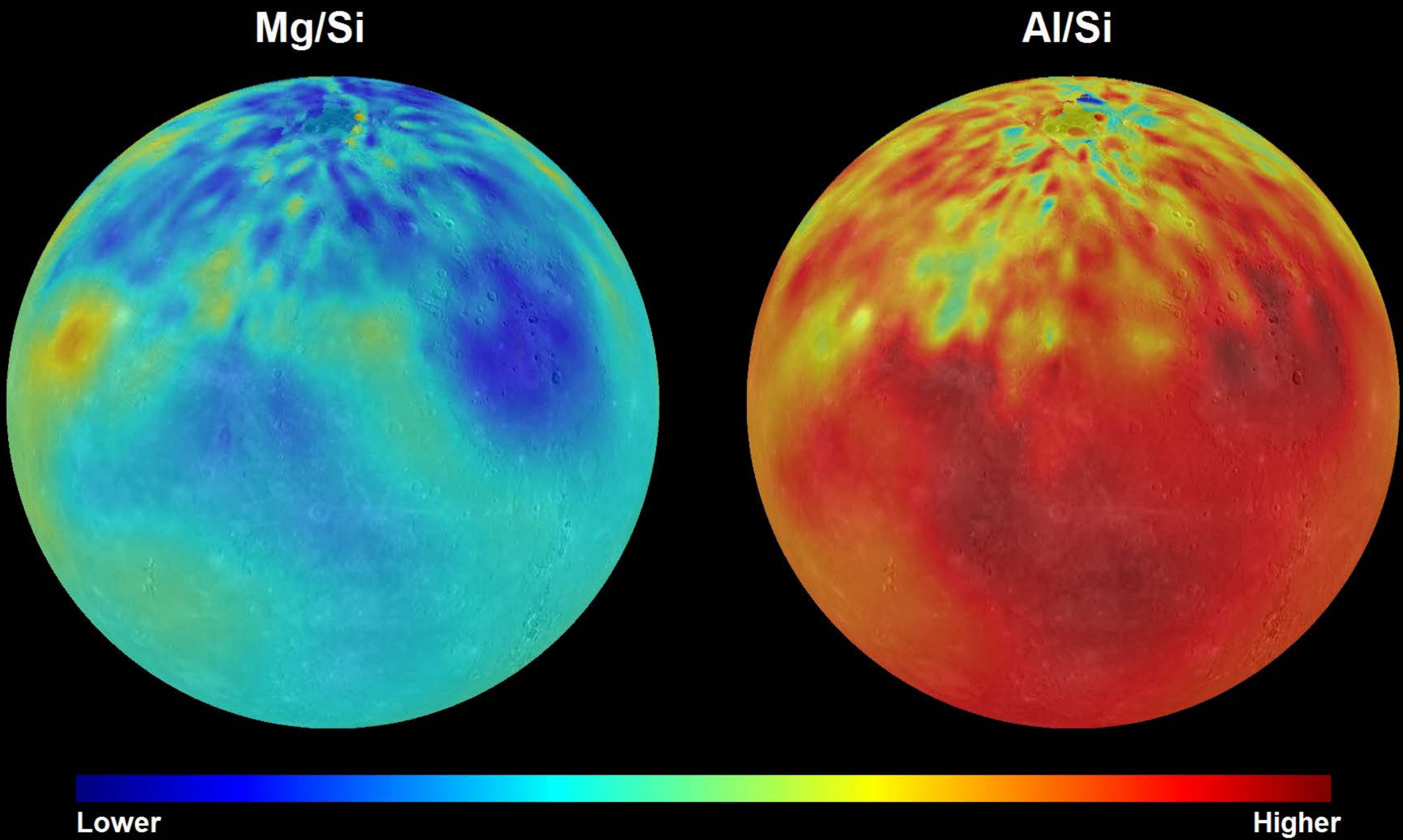
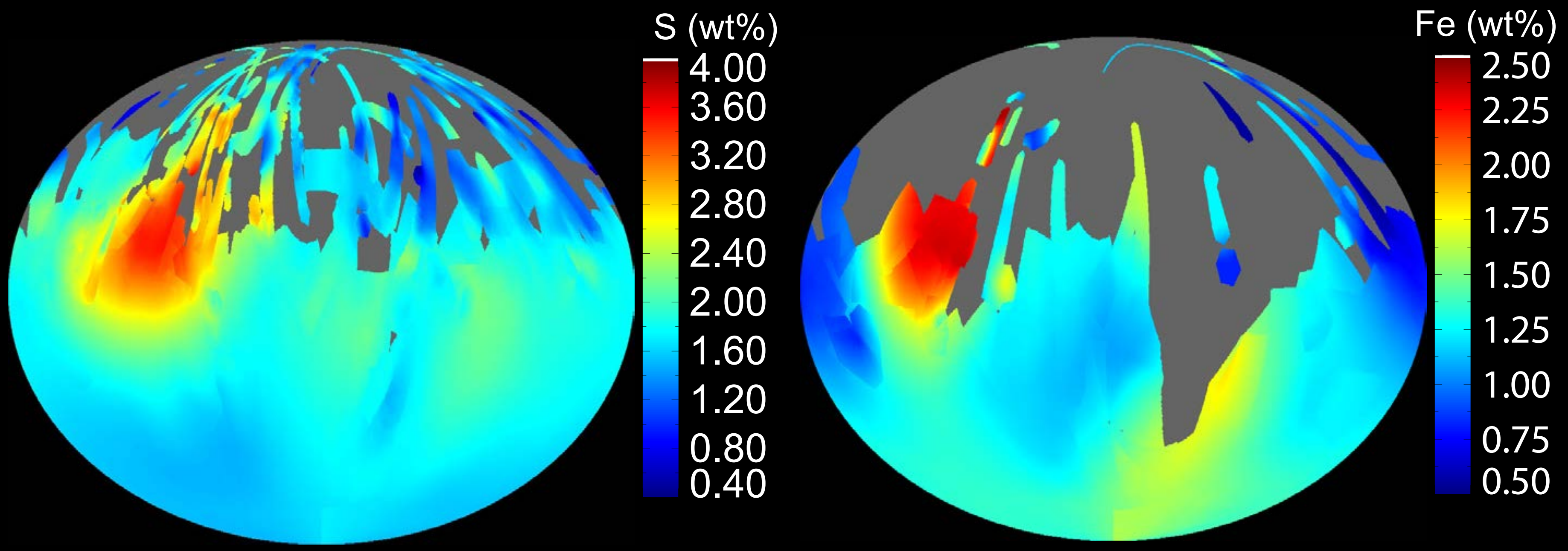
Major elements on Mercury



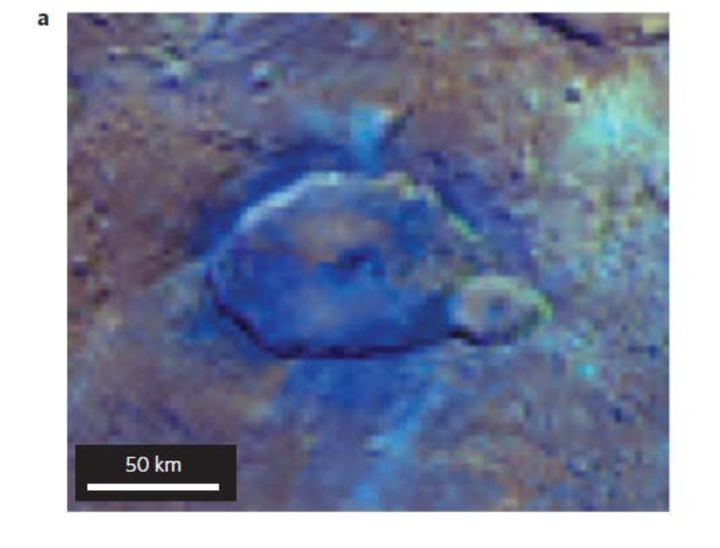
Weider et al. EPSL, 2015

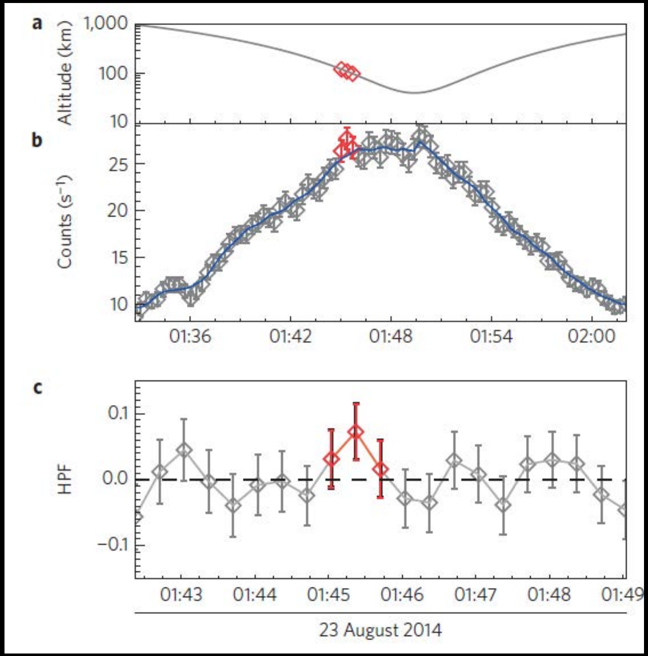
High Sulfur, Low Fe



- S much higher; Fe much lower than other terrestrial planet crusts
    - Earth's Crust: ~300 ppm S, 5 wt% Fe
- Indicates formation under much less oxidizing conditions than other planets

Carbon on Mercury!





Peplowski et al. *Nature Geoscience* 2016

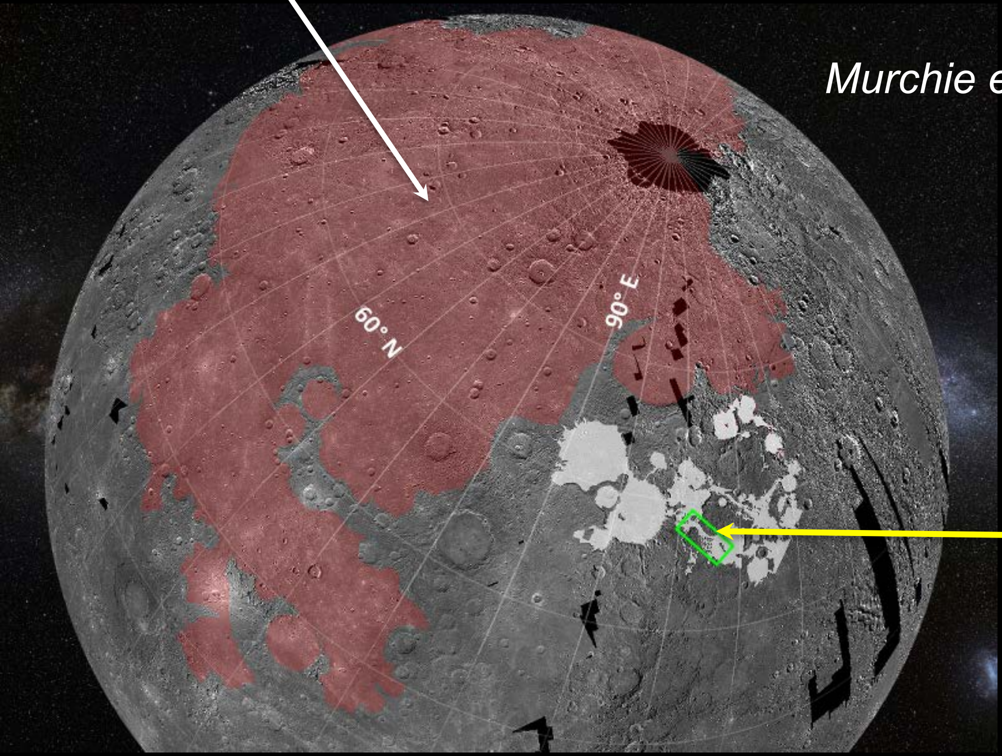
- Mercury very dark; darkest materials excavated from deep in crust
- Low-altitude neutron measurements, spectra most consitent with graphite
  - average ~1 wt% graphite at surface
  - Buried remnant of Mercury's first crust ??

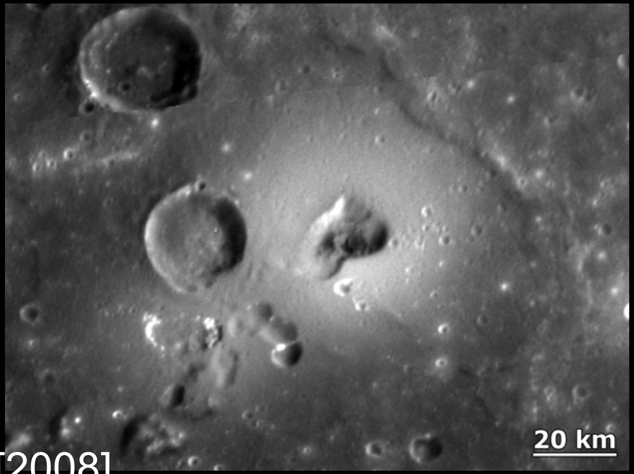
Mercury is a volatile-enriched, chemically reduced planet

- Rules out many pre-MESSENGER formation models involving very high temperatures
  - High-temperature accretion
  - Evaporation of larger mantle by bright early Sun
  - Stripping of larger mantle by giant impact?? [still viable, but no reliable geochemical predictions]
- Mercury made of different mix of materials than other terrestrial planets

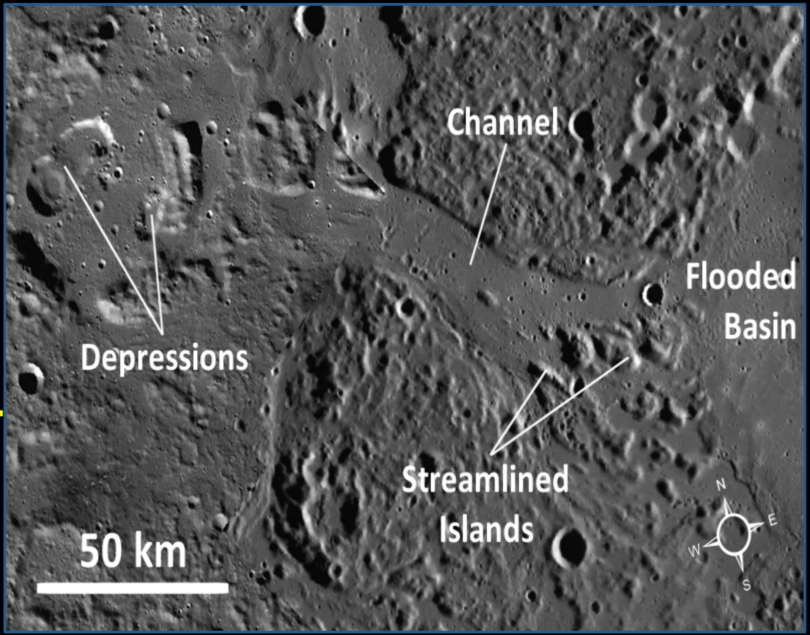
Geologic History: Widespread Volcanism

Northern Plains





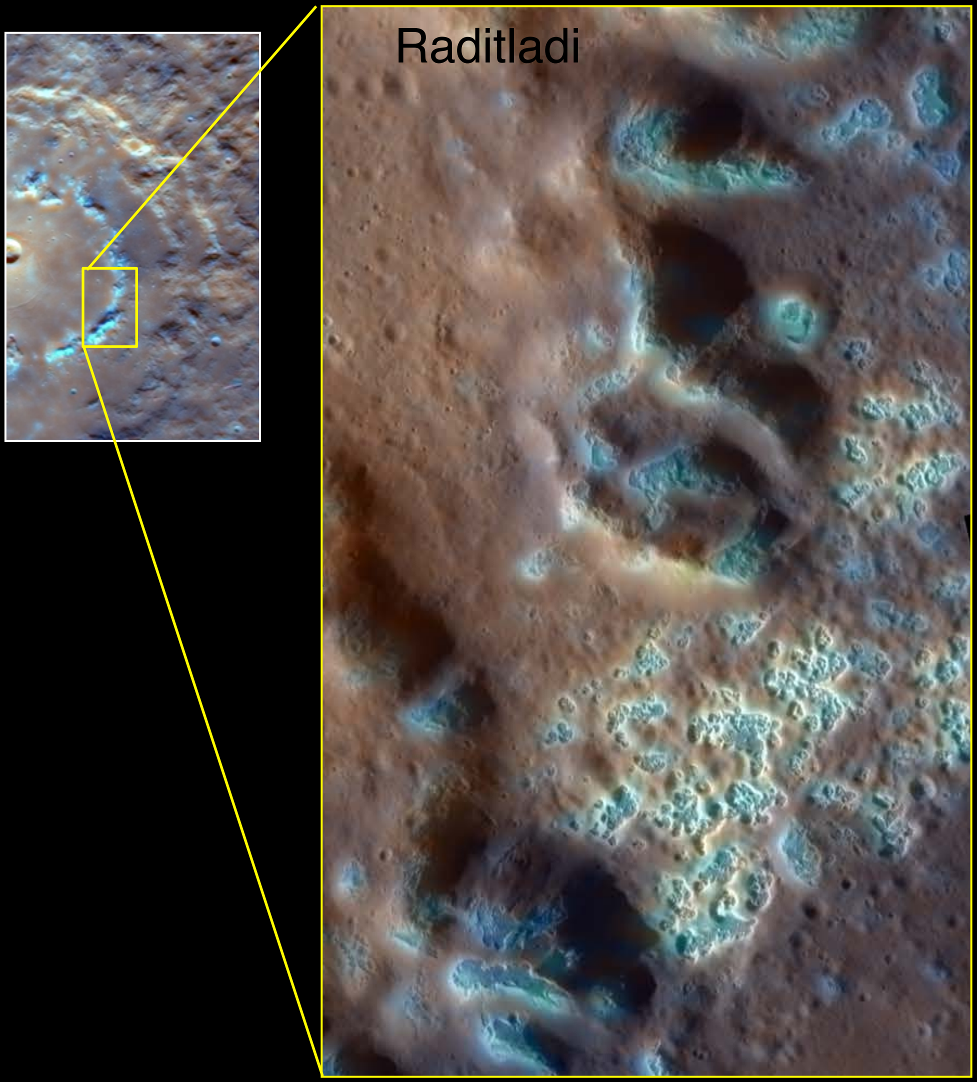
Murchie et al. [2008]



Head et al. [2011]

New Landform: "Hollows"

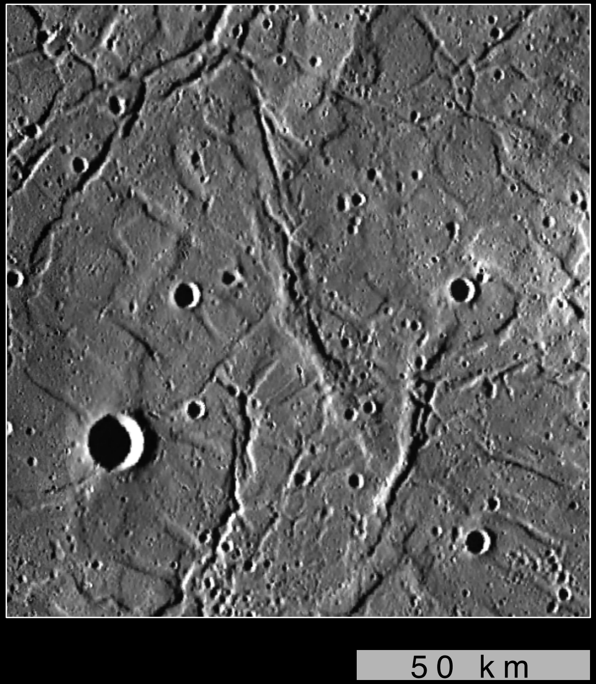
- Bright deposits within impact craters show fresh-appearing, rimless depressions, commonly with halos.
- Formation from recent volatile loss?



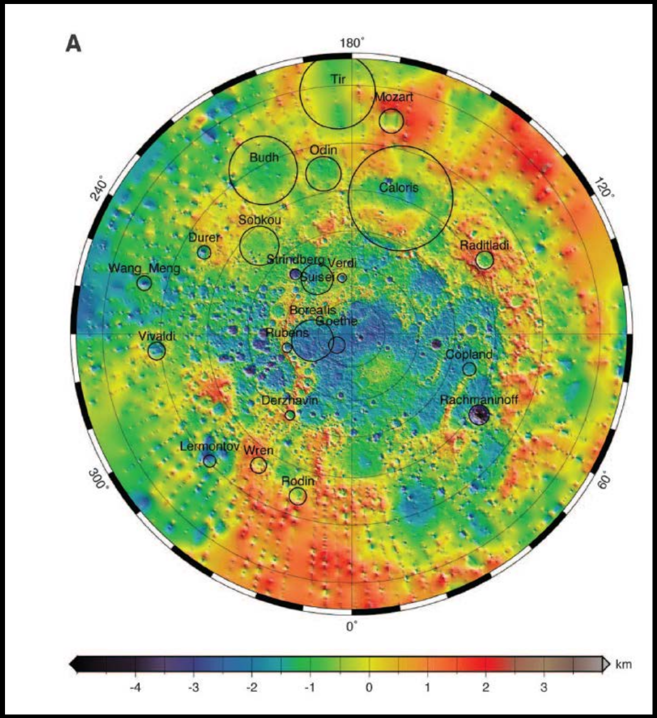
[Blewett et al., 2011]

Tectonics

- Mercury covered with "lobate scarps" (cliffs)
- Due to contraction of planet as it cooled



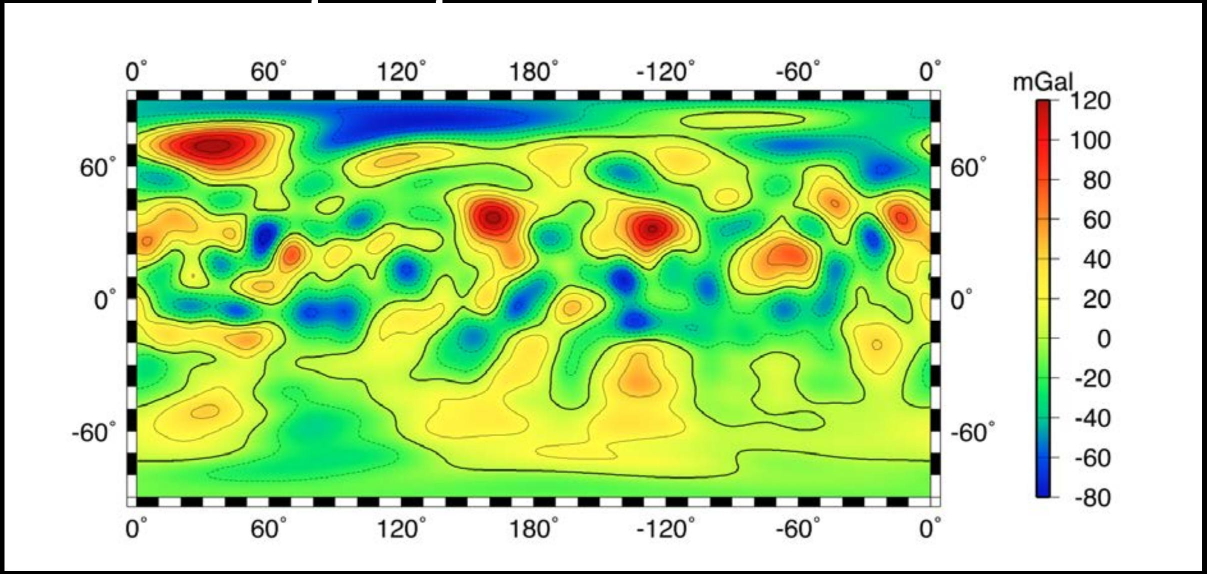
- Detailed analysis of MESSENGER data indicates much more contraction than previous work (Byrne et al. 2014)



Zuber et al. Science [2012]

Mercury Geophysics

- Radio Science combined with topography (left, from laser altimetry) to infer gravity map (below)
- Use to constrain interior

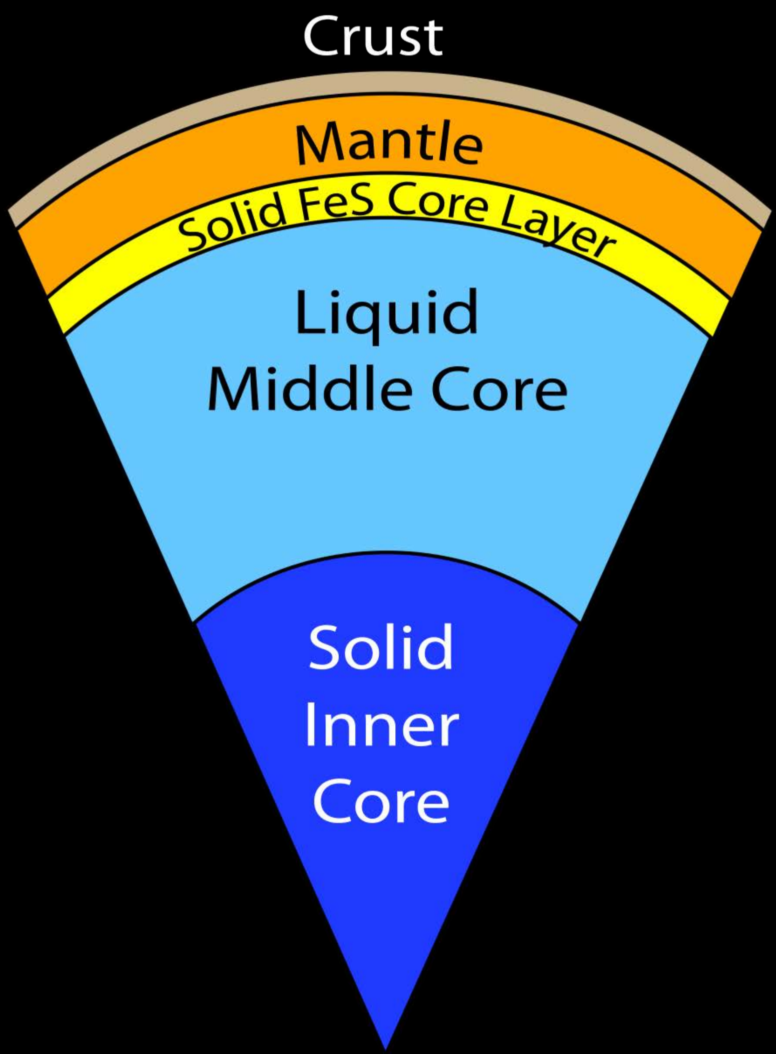


Smith et al. Science [2012]

Internal Structure

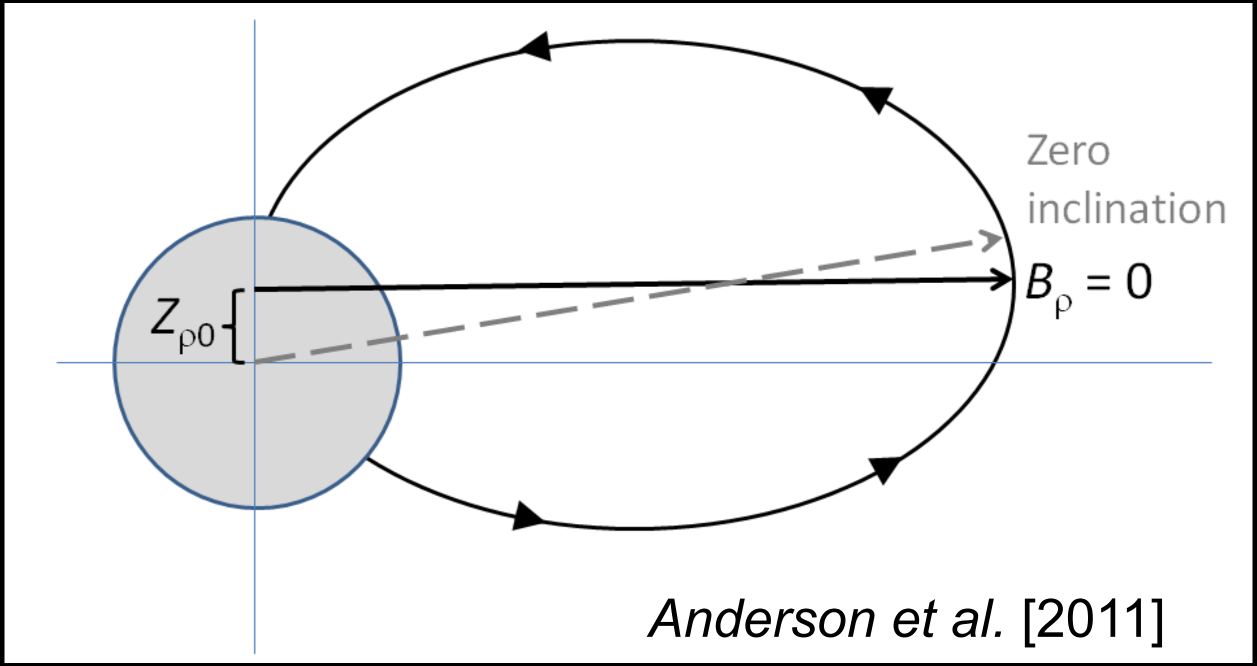
- Model of interior based on gravity field
  - Based on millions of internal structure models (Smith et al. 2012, Hauck et al. 2013)
  - Top of liquid core at r=2020 ± 30 km [R_{planet}=2440 km)

- High density (FeS) layer at base of mantle not required but consistent with data and may be expected for highly reduced planet



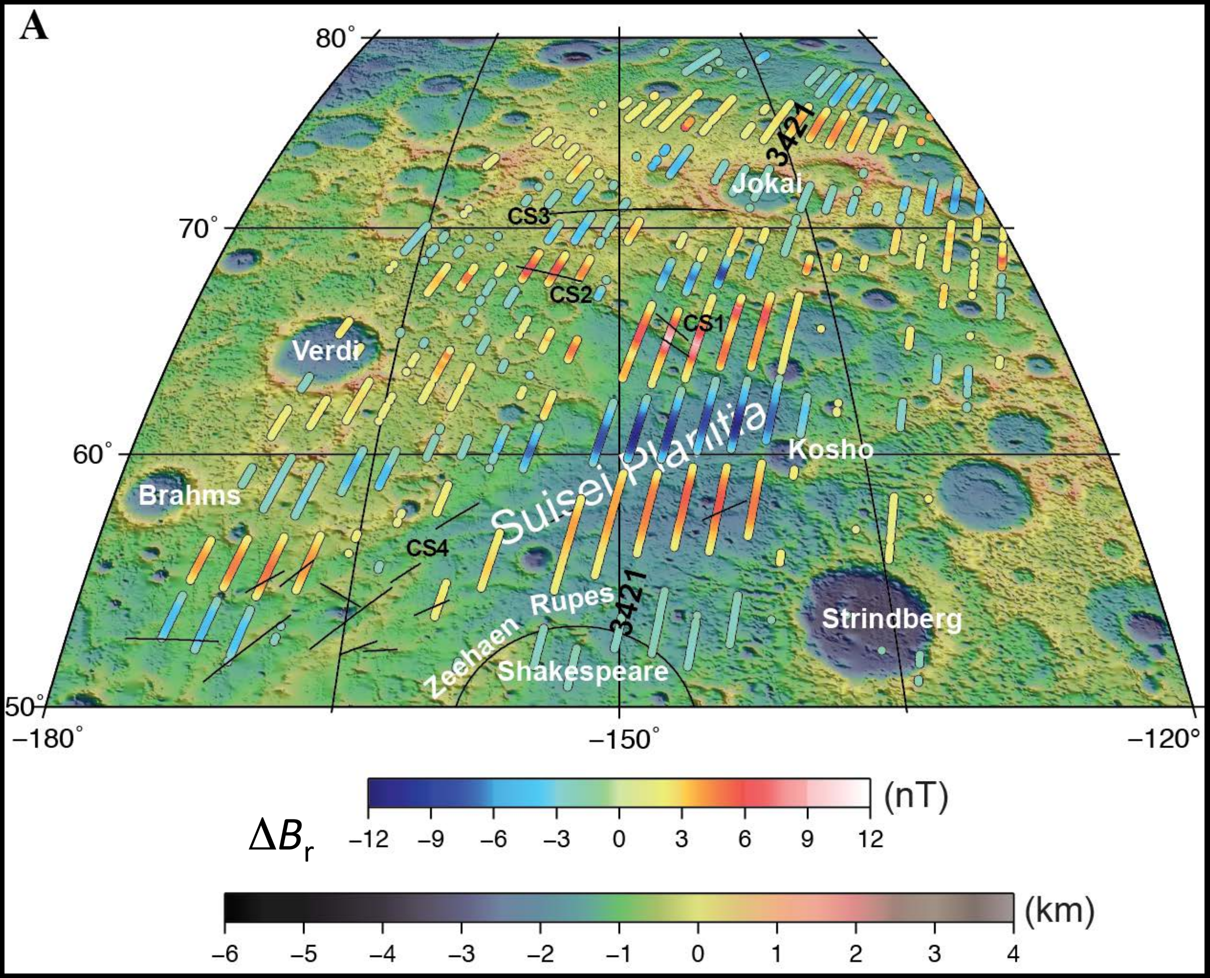
Hauck et al. [2012]

Magnetic Field: Dipole with Equator Offset



- Magnetic field is dipolar and of the same sense as that of the Earth, but displaced northward from the planet center by 480 km
- Large offset is unprecedented in the solar system and puts constraints of the generation mechanism

Remanent Crustal Magnetism

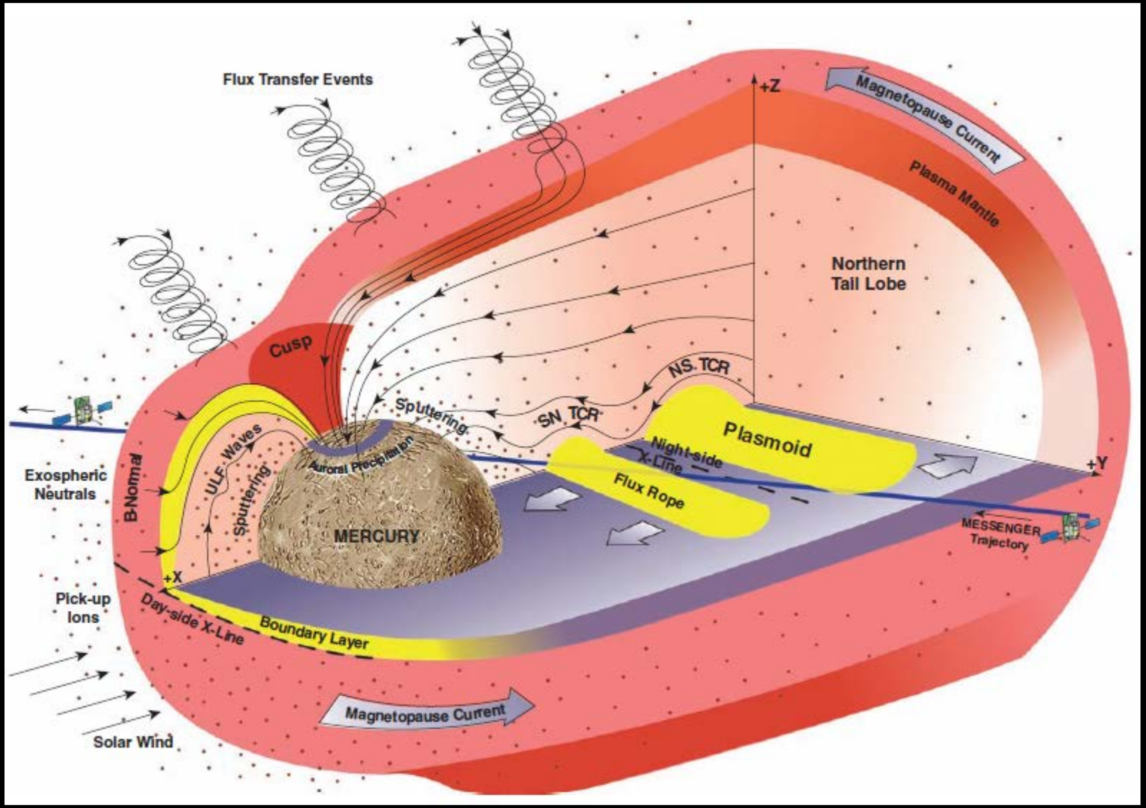


Johnson et al. 2015

- At low altitude (<60 km), saw magnetic field variations from surface –preserved in crust
- Thermal preservation of magnetization over ~4 Gyr!

Mercury's Magnetosphere

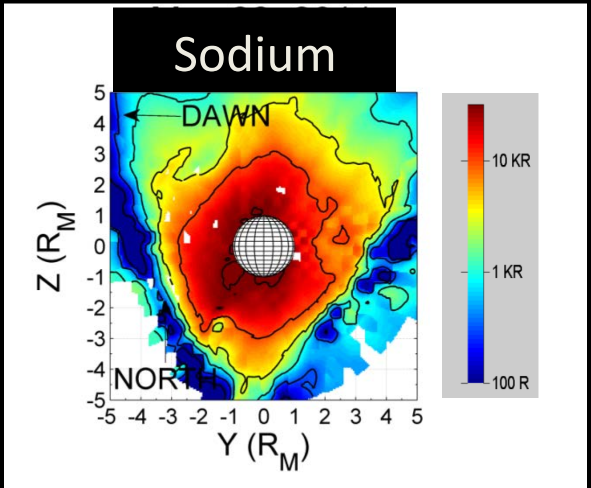
- Interaction of Mercury's weak magnetic field with solar magnetic filed leads to compelx and dynamic "magnetosphere"
  - Playground for space plasma physicists

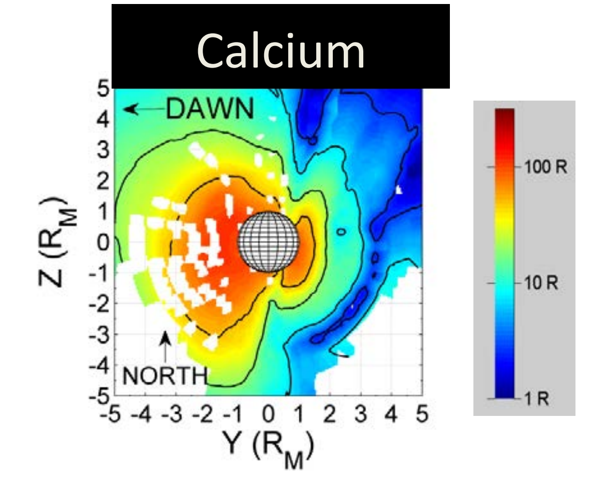


Slavin et al. [2009]

Mercury's Exosphere

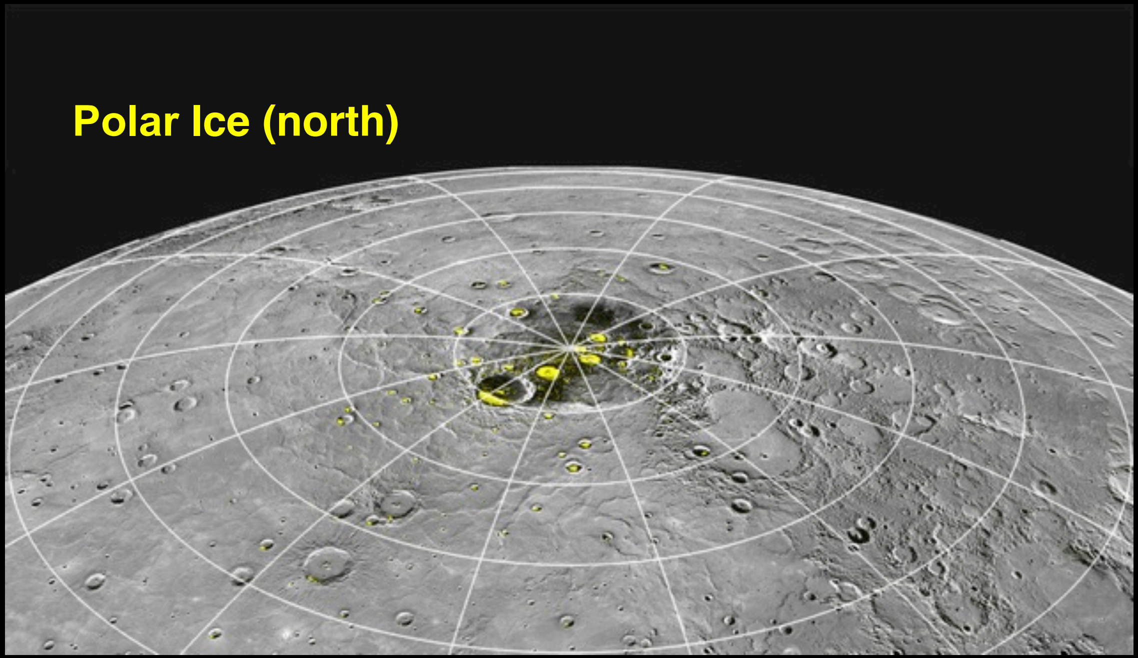
- Na, Ca, Mg most abundant species
- Asymmetries in distributions: different source mechanisms
  - Na uniformly distributed
  - Ca shows dawn enhancement
  - Both show seasonal variability





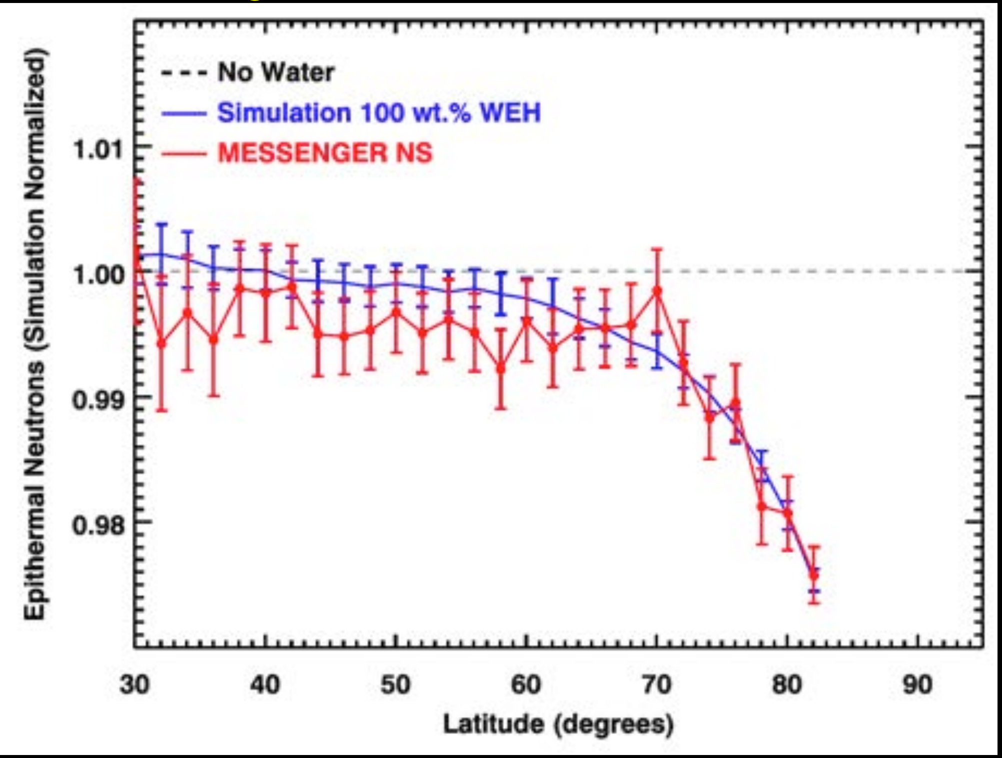
Vervack et al., 2011, Killen et al., 2012, Burger et al., 2012, 2014; Merkel et al., 2012

Mercury’s Polar Deposits



- Deposits with radar characteristics of water ice discovered in polar craters by ground-based astronomy in 1992.
- Imaging of polar regions confirms that radar-bright deposits occur in permanently shadowed regions
- Thermal modeling indicates ice/organic stability where deposits located

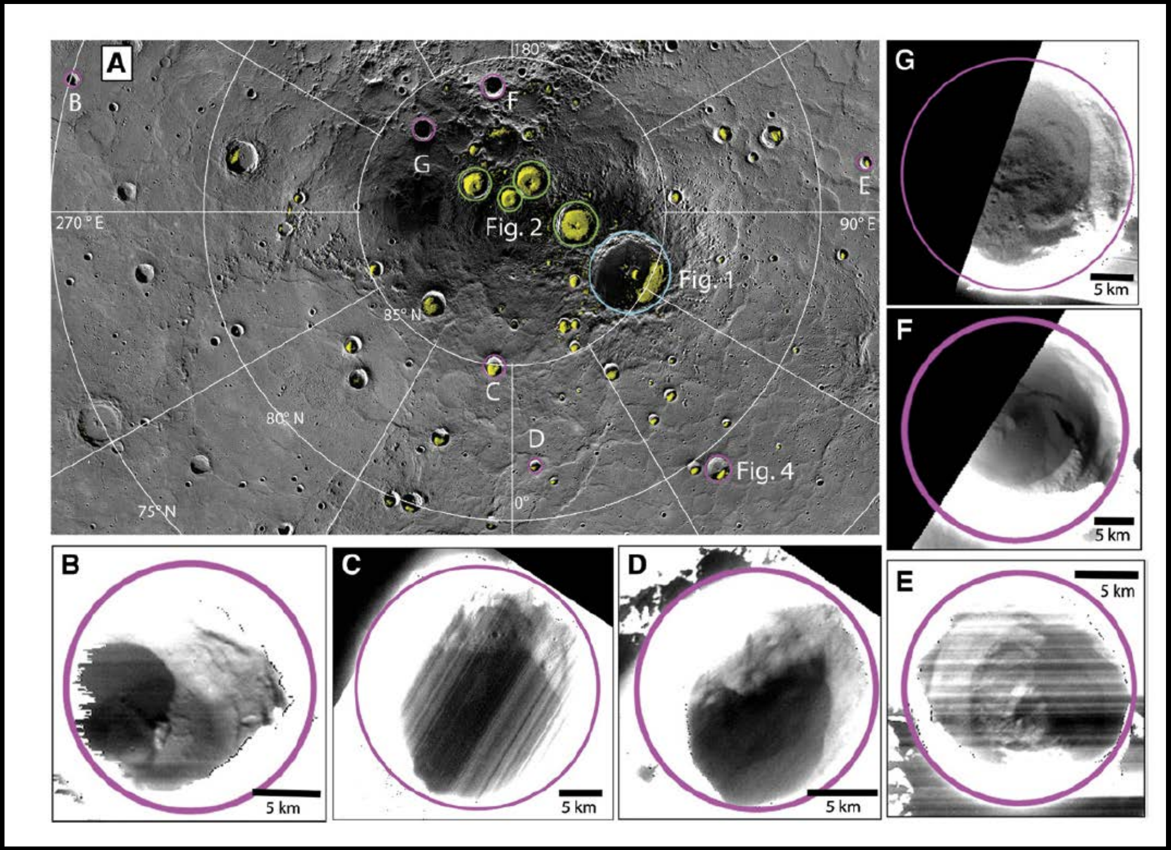
Mercury's Polar Deposits



- Neutron emissions sensitive to hydrogen
- Decrease at Mercury's North pole quantitatively matches expectation if deposits are water ice

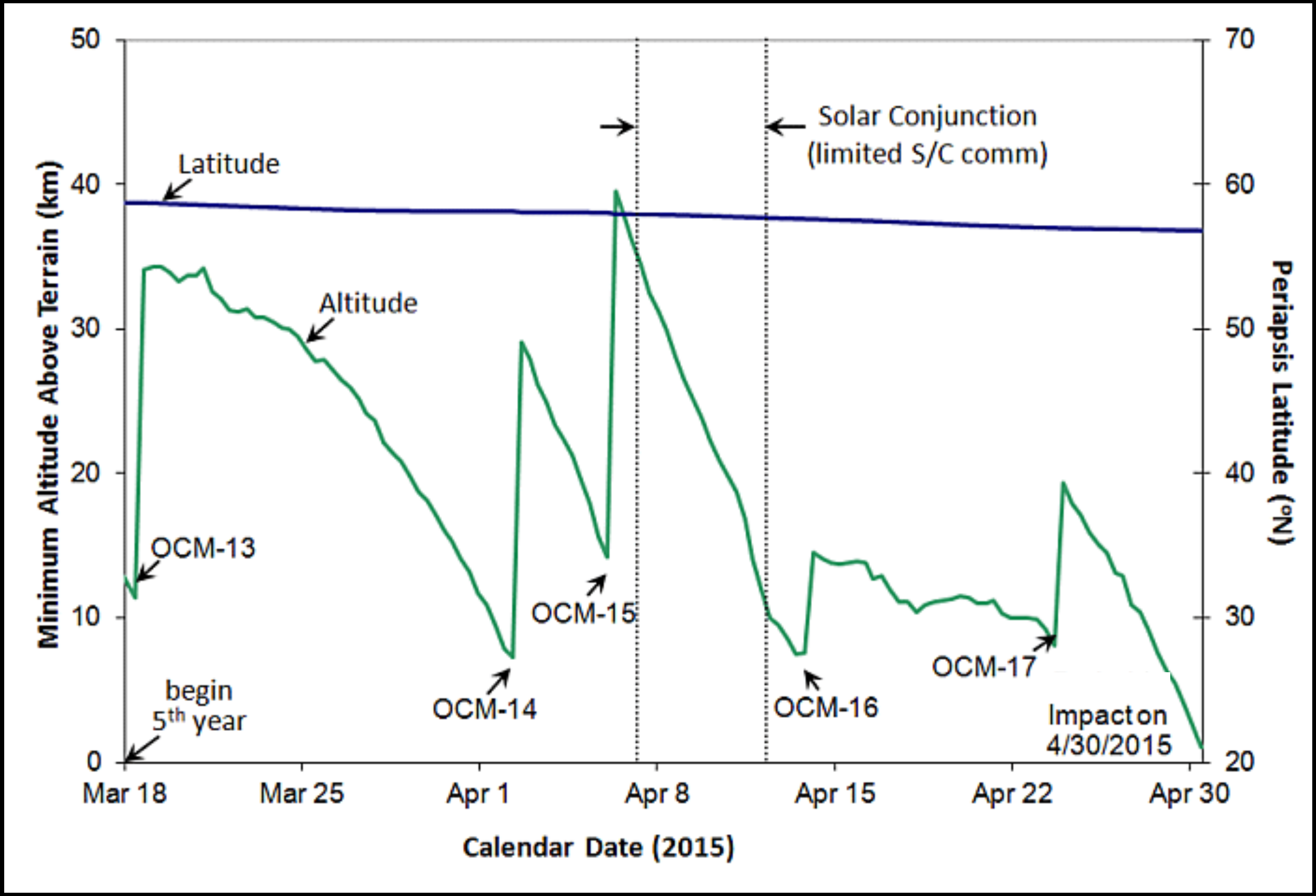
Lawrence et al., Neumann et al., Paige et al. Science [2013]

Mercury's Polar Deposits



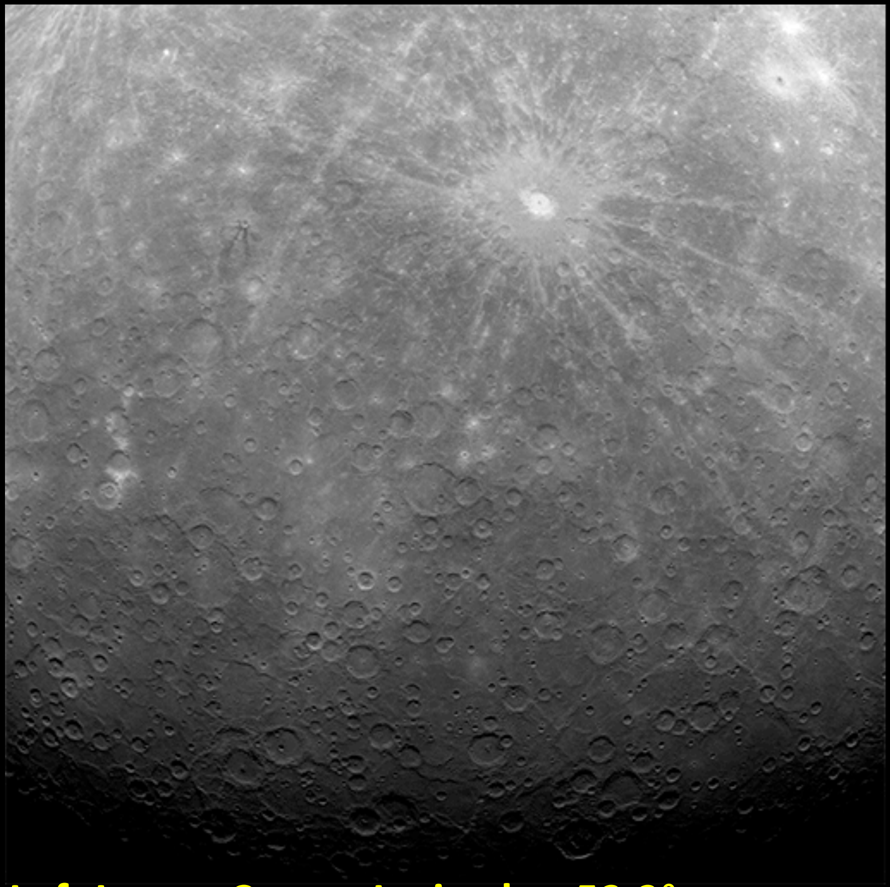
- Deep MESSENGER imaging also reveals brightness variations in deposits (Chabot et al , 2014)

End of mission



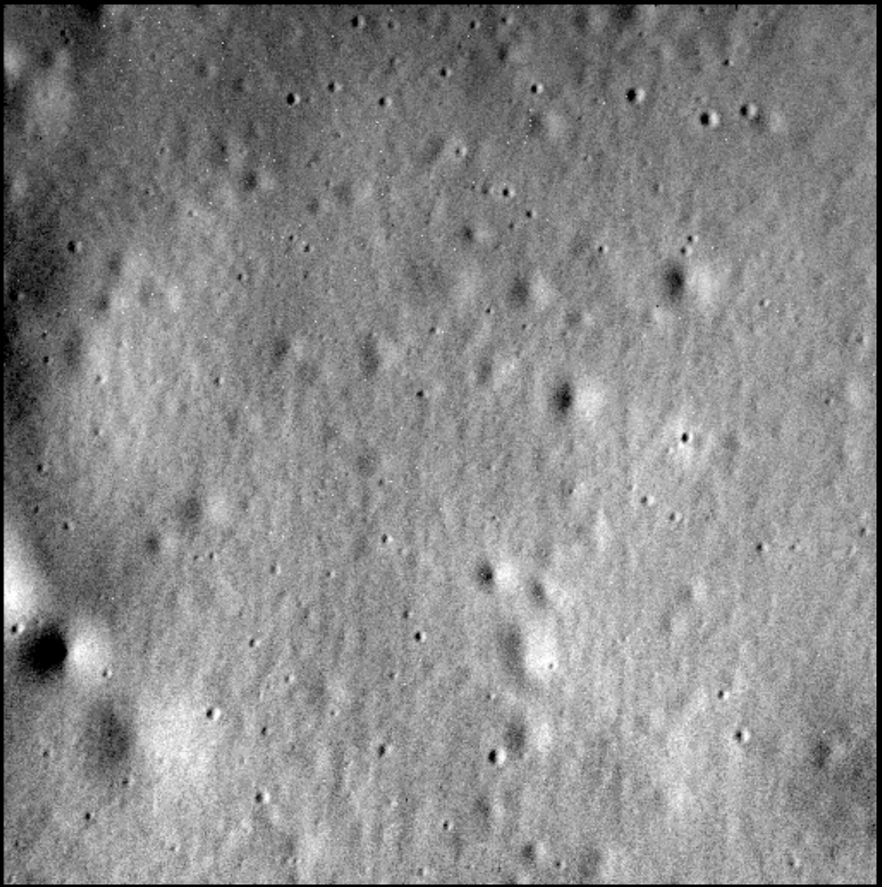
- First use of helium as spacecraft propellant!

FIRST



Left Image Center Latitude: -53.3°
Left Image Center Longitude: 13.0° E
Left Image Resolution: 2.7 kilometers/pixel
Left Image Scale: The rayed crater Debussy has a diameter of 80 kilometers (50 miles)

LAST

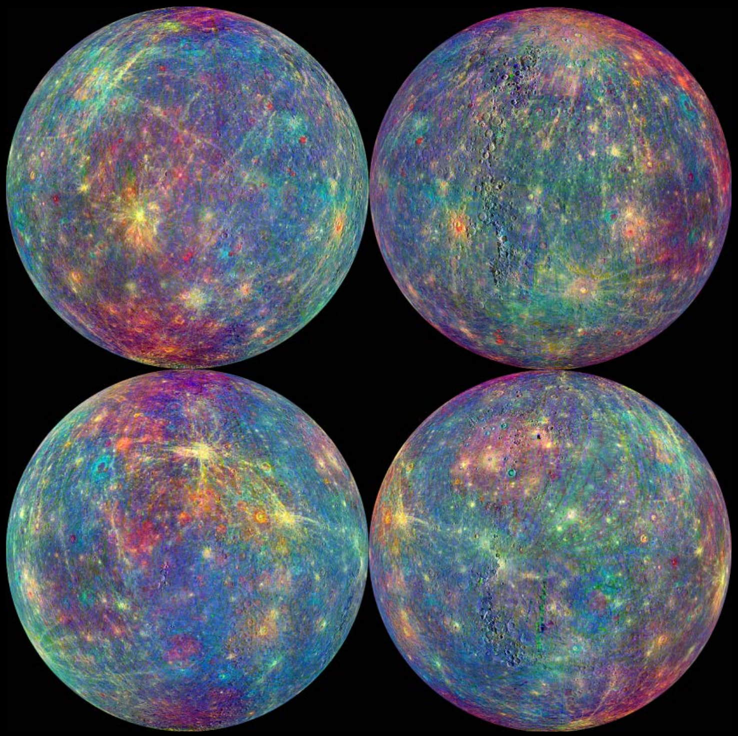


Right Image Center Latitude: 72.0°
Right Image Center Longitude: 223.8° E
Right Image Resolution: 2.1 meters/pixel
Right Image Scale: This image is about 1 kilometers (0.6 miles) across

Acknowledgements

- MESSENGER Science Team, Engineers and Mission Controllers

MESSENGER at Mercury



- MESSENGER was an extraordinarily successful mission
- Despite its small size, Mercury is a weird and wonderful world.
  - Different in fundamental ways from other terrestrial planets
  - May provide valuable information for extrasolar planets

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